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A METHOD FOR ESTIMATING FUGITIVE PARTICULATE EMISSIONS FROM HAZARDOUS WASTE SITES

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16. ABSTRACT

Control techniques are reviewed for applicability to fugitive particulate emissions from hazardous waste sites. Techniques judged applicable include chemical stabilization (40 to 100 percent efficiency, \$520/acre-yr to \$2,720/acre-yr), wet suppression (25 to 90 percent efficiency, \$365/acre-yr to \$1,270/acre-yr), physical covering (30 to 100 percent efficiency, \$0.01/m^2 to \$65/m^2), vegetative covering (50 to 80 percent efficiency, \$0.11/m^2 to \$3.96/m^2), and windscreens (30 to 80 percent efficiency, \$18.01/m^2 to \$26.90/m^2 of screen). Reducing vehicle speed on unpaved roads can reduce emissions by 25 to 80 percent depending on initial conditions.

Supporting reviews are included for soil characteristics, emission factors, and dispersion processes that generate and distribute fugitive particulate matter. A method is described to estimate degree of contamination (DOC) of soil particles based on the contaminating chemical's water solubility and the soil's organic carbon content. A first-order decay process is included. Five example sites are described and estimates made of uncontrolled and controlled downwind concentrations of hazardous constituents. Annual averages are in the attogram to nanogram per cubic meter range. Ranges for control and efficiency costs for each site are included.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazaradous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This document describes the sources and controls for fugitive dust emissions from hazardous waste treatment, storage and disposal facilities, and presents procedures for estimating controlled and uncontrolled dust emissions. A method for estimating the degree of soil contamination is described as part of the source characterization. The intended audience for this document includes those involved in the review of new and existing hazardous waste facilities.

For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

Thomas R. Hauser, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

Control techniques are reviewed for applicability to fugitive particulate emissions from hazardous waste sites. Techniques judged applicable include chemical stabilization (40 to 100 percent efficiency, \$520/acre-yr to \$2,720/acre-yr), wet suppression (25 to 90 percent efficiency, \$365/acre-yr to \$1,270/acre-yr), physical covering (30 to 100 percent efficiency, \$0.01/m^2 to 65/m^2), vegetative covering (50 to 80 percent efficiency, \$0.11/m^2 to \$3.96/m^2), and windscreens (30 to 80 percent efficiency, \$18.01/m^2 to \$26.90/m^2 of screen). Reduction of vehicle speed on unpaved roads can reduce emissions by 25 to 80 percent, depending on initial conditions.

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This report was submitted in fulfillment of Contract Number 68-03-3149, Work Assignment Number 7-1 by Research Triangle Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from April to September 1984, and the work was completed as of September 30, 1984.

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SECTION 1
INTRODUCTION

Particulate emissions may be significant contributors to offsite contamination. Liquid hazardous materials are adsorbed by surrounding soil particles that subsequently are windborne and inhaled by exposed pupulations or deposited on land or water used for food production. Similarly, solid materials may become eroded or windborne and eventually inhaled or deposited.

Examples of sites that can contribute to windborne contaminants include open waste piles, unpaved haul roads, landfills of various configurations, and dried lagoons. For each, some combination of mechanisms must allow a contaminating material to be adsorbed by containing or surrounding soil and dispersed in prevailing winds.

Methods of controlling fugitive particulate matter emissions range from preventing contaminants from reaching the soil or from being eroded (if solid), to planting vegetative covers that prevent soil movement. A site can be covered with benign material or crustal agents used to bond soil particles together to prevent soil movement. To determine overall control effectiveness, one must be able to estimate emission factors (controlled and uncontrolled) from sites of interest, degree of contamination (DOC) of emitted particles, and dispersion of particles.

The major objective of this work is to identify and evaluate individual control options for treatment, storage, and disposal facilities (TSDF's). A supporting objective is to provide data and estimation procedures in order to determine degree of soil contamination at TSDF's.

To reach these objectives, the report first describes soil and site characteristics and the factors that lead to fugitive emissions. Soil contamination and emission rates are discussed next, and example TSDF's are introduced. These TSDF's are used later as a basis for emission estimates and control applications. Control techniques are described in depth, followed by a discussion of their effectiveness and cost. The elements of the report are brought together by estimating emissions at the example TSDF's and describing applicable control methods and their expected efficiency and cost. Limitations of the work and future needs are discussed briefly.

Information for this report was taken primarily from the literature on agricultural, mining, and industrial emissions and from pesticides research. No field work was performed.

SECTION 2
CONCLUSIONS

Many fugitive particulate controls have been found that act by preventing or reducing contact between wind and soil particles. The most common type is some form of liquid, such as asphaltic compounds, that can be sprayed over soil surfaces to form crusts or to bond particles together. Other types include vegetative covers; wind breaks; and physical covers of soil, clay, or artificial materials. Control effectiveness depends on efficiency, longevity of actions, and resistance to wind and other erosive forces. A summary of control costs and efficiencies is given in Table 1. This information, taken from Sections 6 and 7 of the report, was developed from a broad review of control techniques discussed in hazardous waste, solid waste, mining, civil engineering, construction industry, and EPA documents.

Controls may be needed to prevent dispersion of hazardous waste emissions from areas of contamination. These emissions may be hazardous wastes in particle form but are more apt to be soil particles contaminated with the wastes. Few data have been found regarding degree of soil contamination at treatment, storage, and disposal facilities (TSDF's); however, soil contamination by pesticides has been investigated extensively. RTI used the generalized results of these investigations to develop a method for estimating degree of contamination (DOC) of soils from sparingly soluble hazardous waste. The method assumes that all contaminant retention on soil occurs by adsorption from a saturated solution and that all contaminant degradation (prior to particle emission) occurs from a first-order decay process. The only information required to use the method is water solubility for the compound of interest and organic carbon content of the adsorbing soil. If significant degradation of the contaminant is assumed, a value for the first-order rate constant is required. The method is described in Section 4, and five examples of its use at TSDF's are given in Section 8 and Appendix A. Appendix B contains a compilation of information that can be used to estimate DOC for many compounds. Results for the two example TSDF's that could be checked are accurate to about 10 and 35 percent.

Relatively little information has been found regarding site characteristics important for assessing downwind deposition from contaminated fugitive particulate matter. However, for prediction purposes, the several types of sites considered can be generalized to three models: line sources for contaminated roads; flat area sources for typical waste sites, landfills, and dried lagoons; and storage pile sources for waste piles.

Emission factors for the three generalized TSDF models can be generated from existing information about, for example, dusting from coal piles, agricultural sources, or haul roads. Without other appropriate data, a

TABLE 1. SUMMARY OF CONTROL COSTS AND EFFICIENCIES

Site and control technique	Cost estimate ($/yr)	TSP efficiency (%)[a]	Inhalable particle efficiency[b]
40-acre landfill			
1. Chemical stabilization			
a. Partially active, frequent applications	35,500-109,000	75-100	Same
b. Inactive, infrequent application	3,700-9,200	75-100	Same
2. Cover--inactive site			
a. Synthetic film, 5-yr life	43,000-256,000	85-100	Same
b. Hardened foam, 2 in., 5-yr life	93,000	85-100	Same
c. 6-in. soil cover, 5-yr life	16,000	85-100	Same
3. Vegetative stabilization, inactive site			
a. Hydraulic seeding, 10-yr life	12,000	50-80	Lower
b. Above plus topsoil	26,000	50-80	Same
c. Hydraulic seeding plus chemical stabilization	15,700-21,200	85-100	Same
4. Wet suppression			
a. For 1-acre active site	365-1,270	25-90	Higher
b. For entire 40 acres	15,000-51,000	25-90	Higher
Dried lagoon (1 acre)			
1. Chemical stabilization	744	75-100	Same
2. Cover			
a. Synthetic film, 5-yr life	1,000-6,300	85-100	Same
b. Hardened foam, 2 in., 5-yr life	3,400	85-100	Same
c. 6-in. soil cover, 5-yr life	400	85-100	Same
3. Vegetative stabilization			
a. Grade, seed, fertilize, 10-yr life	1,100	50-80	Lower
b. Hydraulic seed, fertilize, mulch, 10-yr life	290	50-80	Lower
c Above plus local topsoil	650	50-80	Same
4. Wet suppression			
a. Water spraying	365-1,270	25-90	Higher
b. With sprinkler system, 10-yr life	1,500	25-90	Higher
Drum storage area			
1. Chemical stabilization			
a. Yearly application	151	75-100	Same
b. Monthly applications	1,800	75-100	Same

(continued)

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TABLE 1 (continued)

Site and control technique	Cost estimate ($/yr)	TSP efficiency (%)[a]	Inhalable particle efficiency[b]
Drum storage area (continued)			
2. Cover			
a. Synthetic film, 5-yr life	50-290	85-100	Same
b. Dome cover, 10- to 20-yr life	11,000-16,000	Up to 100	Same
3. Vegetative stabilization			
a. Grade, seed, fertilize, 10-yr life	52	50-80	Lower
b. Above plus topsoil	68	50-80	Same
Unpaved road (0.5 mi)			
1. Chemical stabilization	22,000-33,000	40-96	Same
2. Cover			
a. 3 to 6 in. of gravel, 5-yr life	5,000-9,200	30	Lower
b. Pave, 3 in., 10- to 20-yr life	6,500-8,500	85	Same
c. Road carpet	4,900	45	Same
3. Wet suppression	20,500-31,500	50	Higher
Waste pile (1.8 acres)			
1. Chemical stabilization--active site	1,600-4,900	75-90	Same
2. Cover			
a. Synthetic film, inactive site, 5-yr life	2,000-12,000	85-100	Same
b. Above plus tension cables, auger feed, active	52,000-79,000	85-100	Same
c. Hardened foam cover, inactive site, 5-yr life	5,300	85-100	Same
3. Vegetative stabilization			
a. Grade, seed, fertilize, 10-yr life	2,000	50-80	Lower
b. Hydraulic seeding, mulch, 10-yr life	540	50-80	Lower
c. Above plus topsoil	1,200	50-80	Same
4. Windscreen, 10-yr life	3,200-12,400	30-80	Lower
5. Wet suppression	660-2,600	25-90	Higher

[a] Percent reduction in total suspended particles.

[b] Expected control of inhalable particles relative to TSP (higher, lower, or the same).

modified version of the wind erosion equation (WEE) can be used to estimate soil lost to wind forces. This equation, based on soil conditions, climatic conditions, and land cover, predicts tons per year of soil lost from 1 acre of land.

Fugitive emission factors for particles and selection of appropriate factors for the various kinds of TSFD's are discussed in Section 5. The method for combining particle emission rate with DOC to obtain a contaminant emission rate is described in Appendix A.

Controlled emissions can be estimated similarly to uncontrolled emissions. Emission factors are derived from control efficiency data (or estimates) and applied as described above.

It should be emphasized that no actual particulate field measurements were made at hazardous waste sites. All the data and estimation procedures presented are based on research at non-hazardous fugitive particulate sources. It is felt that much of the fugitive particulate emission data from non-hazardous sources is applicable to hazardous waste sites, with the exception of the degree of contamination (DOC). Degree of contamination is the percentage of the fugitive particulate that is toxic or hazardous, and is site specific. Now that a general understanding of the emission mechanisms, rates, and control techniques has been developed, field measurements can be performed to validate this information.

SECTION 3
FACTORS AFFECTING FUGITIVE EMISSIONS

Estimating fugitive particulate emissions and resulting downwind ground-level contaminant concentration is a two-step process: (1) determining the rate of emission or entrainment of particulates into ambient air, and (2) determining the atmospheric dispersion of emitted material and resulting downwind concentrations. The theory of atmospheric dispersion and gaussian diffusion models has been relatively well developed (Slade, 1968), and numerous computer models have been developed to predict downwind air and surface concentrations through point, line, or area emission sources. Emissions from TSDF's must be estimated based on available data from other similar fugitive particulate emission sources such as unpaved roads, storage piles, and open-area sources.

Fugitive emissions from a hazardous waste facility or an open dust source may depend upon:

- Soil characteristics such as particle size, organic content, moisture, soil type and texture, and erodibility. Soil properties determine ease or propensity of particle entrainment.

- Climatic conditions such as mean wind velocity, humidity, and extent of precipitation and solar influx. These parameters affect long-term average soil moisture content.

- Destabilizing factors such as mechanical activity and vehicle traffic onsite. Such factors may change the soil surface characteristics and/or contribute mechanical energy for particle entrainment. Mechanical activity tends to restore a site's "erosion potential."

- Extent of nonerodible elements at a site determine its erosion potential. Elements such as clumps of grass or stones on the surface consume part of the shear stress of the wind, which otherwise would be transferred to erodible soil.

Each of these factors is discussed below.

3.1 SOIL CHARACTERISTICS

Lutton et al. (1979) describe soils as being classified by either the Unified Soil Classification System (USCS) or the U.S. Department of Agriculture (USDA) Classification System. The USCS (Figure 1) is engineering oriented, grouping soils by particle size and plasticity characteristics. The USDA (Figure 2) classifies by texture only, i.e., percentages of gravel, sand, silt, and clay. Figure 3 shows the grain-size difference between the USDA and USCS systems, while Figure 4 shows the two systems superimposed. The classifications can be interchanged as given in Tables 2 and 3.

Cowherd et al. (1984) describe the importance of surface material texture. Susceptibility of exposed soil or surface material to wind erosion and mechanical entrainment is determined by its dry particle size distribution. Wind forces transport soil in three ways: saltation, surface creep, and suspension. Saltation describes particles from about 75 to 500 μm that bounce and jostle each other near the air-surface interface. Particles moved by surface creep are about 500 to 1,000 μm. They are propelled near the ground by wind stress and the impact of the smaller particles transported in saltation. Particles smaller than about 75 μm are moved by suspension and tend to follow air currents. The upper size limit of silt particles (75 μm in diameter) is both the smallest particle size routinely analysed by dry sieving and the largest particle size normally suspended in air. The threshold wind speed for saltation, which is the basis for wind erosion, depends on soil texture, with 100 to 150 μm particles having the lowest threshold speed.

Surface moisture strongly affects dust emissions. Water suppresses dust by forming cohesive moisture films among individual grains of surface material.

The surface moisture content is a variable that depends on capillary forces in the soil and boundary conditions at the surface, such as wind velocity, temperature, and air humidity. A soil's ability to become cohesive in the presence of water depends on the surface charges on soil particles as well as surface tension effects. The drying of soils is a complex process involving moisture transport to the surface from within the soil.

When wetted, fine soil particles can form a surface crust that tends to retain soil moisture and resist erosion. Modulus of rupture and thickness of crust measurements indicate the degree of protection afforded to an underlying soil. A soil lacking surface crust is susceptible to wind erosion.

When a surface is disturbed, it becomes more erodible because of increased destruction of crusts and vegetation. Nonerodible elements are shattered and new surface fines are exposed. Vehicular traffic alters the surface by pulverizing surface material, and exposing erodible material beneath.

3.2 CLIMATIC CONDITIONS

Three important climate-related factors affecting fugitive emissions are wind velocity, atmospheric stability, and soil moisture content. Wind provides the mechanical energy for particle entrainment. A certain minimum

FIELD IDENTIFICATION PROCEDURES (Excluding particles larger than 3 inches and basing fractions on estimated weights)						GROUP SYMBOLS [a]	TYPICAL NAMES
COARSE GRAINED SOILS More than half of material is larger than No 200 sieve size [b]	GRAVELS More than half of coarse fraction is larger than No 4 sieve size	CLEAN GRAVELS (Little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes			GW	Well graded gravels, gravel-sand mixtures, little or no fines.
			Predominantly one size or a range of sizes with some intermediate sizes missing			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines.
		GRAVELS WITH FINES (Appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)			GM	Silty gravels, poorly graded gravel-sand-silt mixtures.
			Plastic fines (for identification procedures see CL below)			GC	Clayey gravels, poorly graded gravel-sand-clay mixtures.
	SANDS More than half of coarse fraction is smaller than No 4 sieve size (For visual classifications, the ¼" size may be used as equivalent to the No 4 sieve size.)	CLEAN SANDS (Little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes			SW	Well graded sands, gravelly sands; little or no fines.
			Predominantly one size or a range of sizes with some intermediate sizes missing			SP	Poorly graded sands, gravelly sands; little or no fines
		SANDS WITH FINES (Appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)			SM	Silty sands, poorly graded sand-silt mixtures.
			Plastic fines (for identification procedures see CL below).			SC	Clayey sands, poorly graded sand-clay mixtures.
FINE GRAINED SOILS More than half of material is smaller than No 200 sieve size. (The No. 200 sieve size is about the smallest particle visible to the naked eye)	IDENTIFICATION PROCEDURES ON FRACTION SMALLER THAN No. 40 SIEVE SIZE						
			DRY STRENGTH (CRUSHING CHARACTERISTICS)	DILATANCY (REACTION TO SHAKING)	TOUGHNESS (CONSISTENCY NEAR PLASTIC LIMIT)		
	SILTS AND CLAYS Liquid limit less than 50		None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity.
			Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			Slight to medium	Slow	Slight	OL	Organic silts and organic silt-clays of low plasticity
	SILTS AND CLAYS Liquid limit greater than 50		Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
			High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays.
			Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity.
HIGHLY ORGANIC SOILS			Readily identified by color, odor, spongy feel and frequently by fibrous texture.			Pt	Peat and other highly organic soils.

Figure 1. Summary of the USC System

Continued

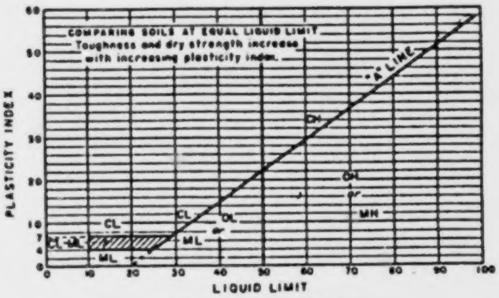
INFORMATION REQUIRED FOR DESCRIBING SOILS	LABORATORY CLASSIFICATION CRITERIA			
Give typical name; indicate approximate percentages of sand and gravel, max. size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses. For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics. EXAMPLE:- Silty sand, gravelly; about 20% hard, angular gravel particles $\frac{1}{2}$-in maximum size; rounded and subangular sand grains coarse to fine; about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM)	Use grain size curve in identifying the fractions as given under field identification	Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows:- Less than 5% GW, GP, SW, SP. More than 12% GM, GC, SM, SC. 5% to 12% Borderline cases requiring use of dual symbols.	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and 3	
			Not meeting all gradation requirements for GW	
			Atterberg limits below "A" line, or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			Atterberg limits above "A" line with PI greater than 7	
			$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and 3	
			Not meeting all gradation requirements for SW	
			Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			Atterberg limits above "A" line with PI greater than 7	
Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; color in wet condition, odor if any, local or geologic name, and other pertinent descriptive information; and symbol in parentheses. For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions. EXAMPLE:- Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML)		 PLASTICITY CHART FOR LABORATORY CLASSIFICATION OF FINE GRAINED SOILS		

Figure 1. (Continued)

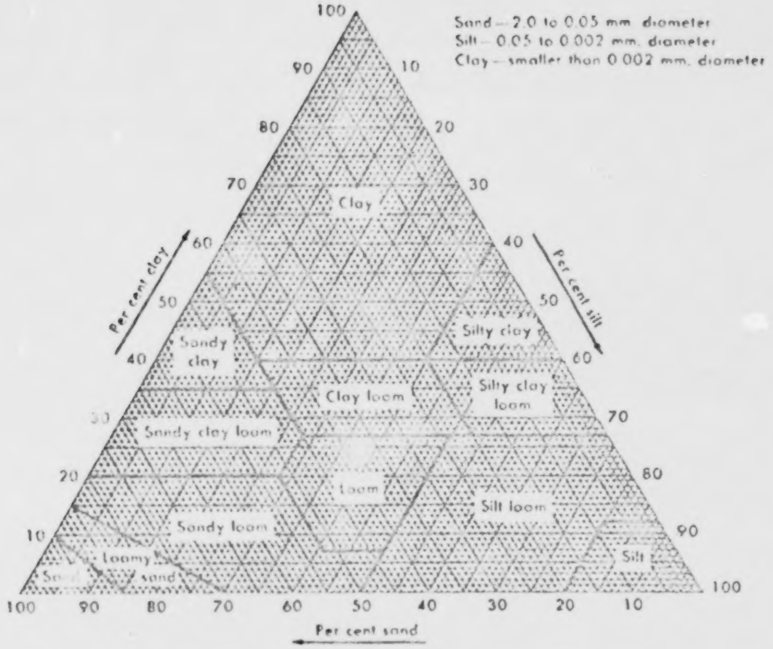


Figure 2. USDA textural classification chart.

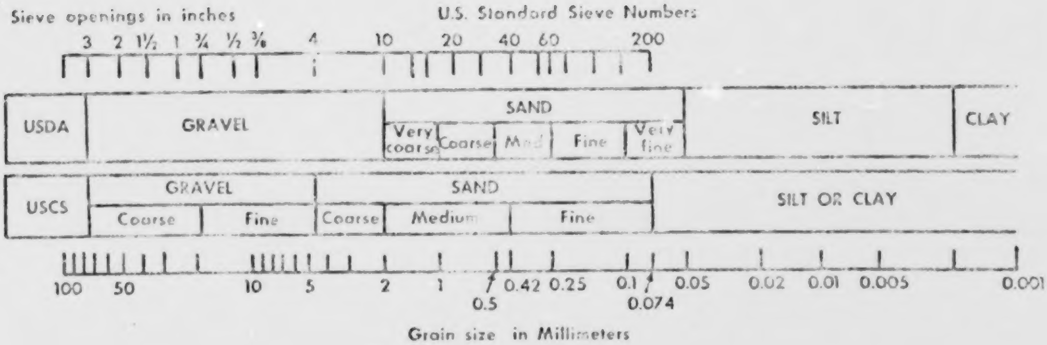

Sieve openings in inches
U.S. Standard Sieve Numbers
3 2 1½ 1 ¾ ½ ⅜
4 10 20 40 60 200
USDA
GRAVEL
SAND
Very coarse
Coarse
Med
Fine
Very fine
SILT
CLAY
USCS
GRAVEL
Coarse
Fine
SAND
Coarse
Medium
Fine
SILT OR CLAY
100 50 10 5 2 1 0.5 0.42 0.25 0.1 0.074 0.05 0.02 0.01 0.005 0.001
Grain size in Millimeters

Figure 3. Comparison of USCS and USDA particle-size scales.

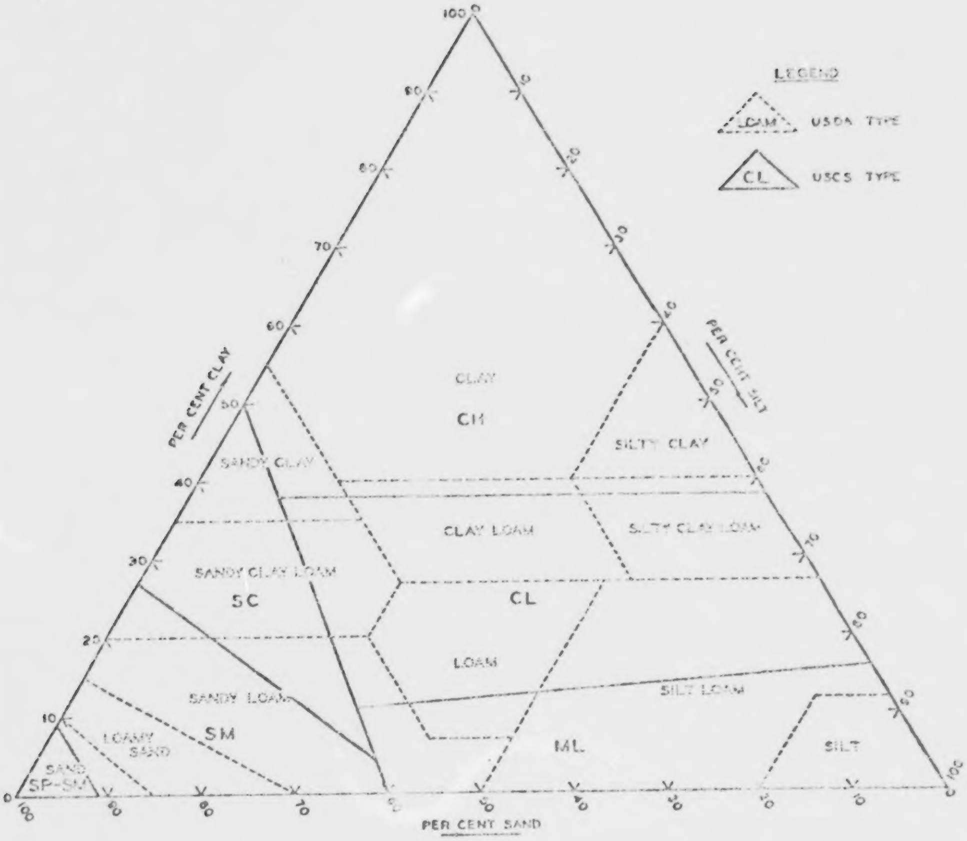


Figure 4. USCS soils superimposed on the USDA textural classification chart. (Correlations are only approximate.)

TABLE 2. USDA TEXTURAL TYPES CORRESPONDING TO USCS SOIL DESIGNATIONS

USCS soil type	USDA soil types
GW	Same as GP (except well graded in grain sizes)
GP	Gravel, very gravelly sand (less than 5 percent silt and clay)
GM	Very gravelly sandy loam, very gravelly loamy sand, very gravelly silt loam, very gravelly loam
GC	Very gravelly clay loam, very gravelly sandy loam, very gravelly silty clay loam, very gravelly silty clay, very gravelly clay
SW	Same as SP (except well graded in grain sizes)
SP	Sand, gravelly sand (less than 20 percent very fine sand)
SM	Loamy sand, sandy loam; sand; gravelly loamy sand and gravelly sandy loam
SC	Sandy clay loam, sandy clay; gravelly sandy clay loam and gravelly sandy clay
ML	Silt, silt loam, loam, sandy loam
CL	Silty clay loam, clay loam, sandy clay
OL	Mucky silt loam, mucky loam, mucky silty clay loam, mucky clay loam
MH	Silt, silt loam (highly elastic, micaceous, or diatomaceous)
CH	Silty clay, clay
OH	Mucky silty clay
PT	Muck, peat

TABLE 3. USCS SOIL TYPES CORRESPONDING TO USDA SOIL TERMINOLOGY

USDA soil type	USCS soil type
Gravel, very gravelly loam sand	GP, GW, GM
Sand	SP, SW
Loamy gravel, very gravelly sandy loam, very gravelly loam	GM
Loamy sand, gravelly loamy sand, sand	SM
Gravelly loam, gravelly sandy clay loam	GM, GC
Sandy loam, gravelly sandy loam	SM
Silt loam, sandy clay loam (with fine-grained sand)	ML
Loam, sandy clay loam	ML, SC
Silty clay loam, clay loam	CL
Sandy clay, gravelly clay loam, gravelly clay	SC, GC
Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay	GC
Silty clay, clay	CH
Muck, peat	PT

wind velocity, often called threshold wind velocity, is required before the soil particles on the surface begin to move. Above this level, particle entrainment may be expected to depend strongly on wind velocity (Sehmel and Lloyd, 1974; Gillette, 1978; Gillette, 1974a). Threshold wind velocity depends upon the size distribution of the soil as well as on the extent of nonerodible elements present.

Wind velocity affects the emission rate as well as the atmospheric dispersion of entrained particles and appears explicitly in the gaussian plume dispersion models. For short-term emission estimates (1 to 2 days), a variation in wind velocity may be used; but for most long-term emission estimates (a month or year), an average value or average frequency distribution is desirable.

Atmospheric stability affects dispersion of the emission plume, determining the extent of the vertical and horizontal transverse and axial spreading of the emitted particulates. Atmospheric stability depends upon the extent of solar insolation, cloudiness, and wind speed. These factors determine vertical thermal gradients and corresponding atmospheric turbulance. Stability is often both seasonal and diurnal. For long-term emission estimates, an average estimate of stability conditions is desirable.

Soil moisture content affects the cohesive forces between soil particles and thus their entrainment. Above a certain soil moisture content, the particles may be bound together so tightly that no fugitive emissions may be expected. Moisture affects cohesiveness differently for different soils. For long-term emission estimates, an average soil moisture content is needed along with frequency of precipitation and may be determined based on Thornthwaite's (1931) precipitation-evaporation (P-E) index. These indices have been compiled for various regions in the United States (Skidmore and Woodruff, 1968). Measured fugitive emissions often correlate with the P-E index (Cowherd et al., 1974; Amick et al., 1974).

Rain or precipitation suppresses fugitive emissions. For certain fugitive emissions such as those from unpaved roads, soil moisture content may not appear explicitly in an emission factor equation. However, in such cases, precipitation frequency usually is considered in order to determine the long-term average emission rate.

3.3 DESTABILIZING FACTORS

Natural or human activities can disrupt stable soil masses to produce particle suspensions in air. Vehicles traveling over unpaved roads can be a major source of fugitive emissions, particularly in arid regions. For example, Levene and Drehmel (1981) report such emissions to be 54 percent of the total annual suspended particulate matter in Phoenix. Cooper et al. (1979) state that dust is displaced from a roadbed by the action of vehicle tires and by surface disturbances from the vehicle's aerodynamic wake. The following lead to wide variability in crude emission factors:

- Vehicle speed, shape, number of wheels, and tire style
- Road surface characteristics
- Meteorological conditions
- Size distribution of the aerosol.

Recent publications on dust from unpaved roads include Rosbury and Zimmer (1983), Russell and Caruso (1983), Morwald (1983), Roberts et al. (1975), PEDCo (1977), and Shrimpton and Shin (1983). Roberts et al. and PEDCo give some information on particle size of road dust aerosols. Emission factors from these publications and other sources are in Section 5.

Waste piles and disposal sites may be shaped. dug, covered, loaded, and unloaded with mechanical equipment such as bulldozers, loaders, and other tracked or large-tired vehicles. As with operations on unpaved roads, these earth moving and scraping activities generate dust clouds that can move offsite. PEDCo (1979) states that emissions from crushed rock storage piles are caused by loading onto the piles (12 percent), equipment and vehicle movement in the storage area (40 percent), loadout from the piles (15 percent), and wind erosion (33 percent). Cooper et al. (1979), Stum (1980), and EPA (1981) discuss storage pile emission factors for activities such as agricultural tilling, which includes mechanical operations that disturb soil.

3.4 NONERODIBLE ELEMENTS

The presence and extent of nonerodible elements determine a site's "erosion potential." Surfaces impregnated with a large density of nonerodible elements behave as having a "limited reservoir" of erodible particles even if the material protected by nonerodible elements is highly erodible (Cowherd et al., 1984). Wind-generated emissions from such surfaces decay sharply with time, as the particle reservoir is depleted. Surfaces covered by unbroken grass are virtually nonerodible. Absence of such elements suggests an unlimited particle reservoir where the wind-generated emissions may be expected to continue at a steady rate for a long time. Presence of such nonerodible elements at a site results in high threshold wind speeds for wind erosion and consequently lower emission rates.

SECTION 4
CONTAMINATION OF SOILS

Soil-chemical interactions are complex and dynamic. Many factors affect a chemical's concentration in the soil: nature, type and profile of soil, contamination level, climate, the chemical's functional properties, and interactions with other chemicals. These factors and the type of contamination determine the degree of contamination at a TSDF.

4.1 FACTORS AFFECTING THE CONCENTRATION OF CHEMICALS IN SOIL

Our understanding of soil-chemical interactions is based largely on laboratory studies that have limitations when applied to the real world. Models that attempt to predict soil adsorption coefficients, for example, in some cases vary by an order of magnitude from observed values (Dragun and Helling, 1981).

The following measures best reflect the nature of soil-chemical interactions: (1) adsorption, (2) mobility, (3) degradation (biological and physical/chemical), and (4) persistence.

Used to describe parameters measured both in laboratories and in the field, these measures are interrelated but not always in clearly definable ways.

The two following sections discuss mobility-adsorption and persistence-degradation interrelations and present basic equations for estimating organic chemical parameters.

For this task, several points should be made prior to a discussion of these measures. The hazardous waste TSDF often differs from the agricultural plot of land, typically the site for studies of pesticide-soil interactions. Hazardous wastes generally are not applied to the soil surface and, therefore, what is known for surface soils should not ordinarily be used directly to predict the fate of chemicals in subsoils.

Fugitive emissions from temporary or permanent cover soils at a hazardous waste site are determined by factors that are difficult to quantify in addition to those parameters mentioned above. For example, volatilized chemicals will percolate upwards and may contaminate (cover) soils not initially mixed with wastes. The presence of solvents changes the mobility of chemicals in soil, and some solvents drastically alter the permeability of clay liners used for containing wastes. Also, it is probably reasonable to assume that surface soils are not water saturated and that saturated models for chemical mobility are not appropriate.

Despite the lack of rigorous data to generate highly predictable models, one can use the available information to relate chemicals on a relative basis to the expected potential hazard.

The mobility of chemicals in soil-groundwater systems is a complex phenomenon consisting of several major processes (Hamaker, 1975). In general, an organic chemical's mobility depends upon mass transport of water, diffusion rate, and adsorption characteristics of the chemical in soil (Guenzi, 1974).

Adsorption is the accumulation of molecules at the surface of a solid phase by the attractive forces of the surface of a solid phase. When adsorption is a significant factor, there is a higher concentration of a chemical in an extremely thin layer at the soil surface than is present in the bulk aqueous solution associated with the soil. The equilibrium adsorption-desorption process is governed by two opposing rate processes. The adsorption rate is the rate at which molecules from the liquid phase transfer into the adsorbed state in the solid phase, and the rate increases as the concentration of dissolved species increases. The desorption rate is the rate of the opposite process; i.e., the rate at which molecules transfer from the adsorbed state at the soil surface into the liquid phase. Equilibrium is established when the rates of these two processes are equal.

Migration in unsaturated soils depends on both the adsorptive qualities of the soil and the rate at which water or other solvents move through the soil. An extremely arid area may not provide enough rain to carry chemicals through the soil even when little adsorption takes place. The chemical may be retained in the soil, occupying external pore spaces rather than being adsorbed, during periods of no rain.

Adsorption is the main process that limits or attenuates a chemical's migration potential in a soil-groundwater system. It is governed by the physical/chemical properties of both the soil and the organic chemical. The important properties of the organic chemical that affect its adsorption by soil are: (1) chemical structure and conformation, (2) molecular size, (3) acidity or basicity of the molecule (pk_a or pk_b), (4) water solubility or octanol/water partition coefficient (usually expressed as log S or log P, respectively), (5) permanent charge, (6) polarity, and (7) polarizability (Helling and Dragun, 1981).

Soil properties affecting adsorption and desorption of organics include organic matter content, type and amount of clay, exchange capacity, and surface acidity (Adams, 1973; Helling, 1970; and Helling and Dragun, 1981). The combined actions of climate and macro- and micro-organisms over long periods on different parent geologic and biotic materials form soils that differ widely in their adsorption characteristics. The amounts and types of clay and organic matter, soil pH, primary and secondary minerals, structure, texture, and exchange capacity vary considerably for U.S. soils.

Soil organic matter is the primary soil property responsible for adsorption of many chemicals. Helling (1970) lists many examples where the organic matter primarily influenced the adsorption of pesticides. Organic matter and clay are the soil components most often implicated in pesticide adsorption. However, the individual effects of either organic matter or clay are not easily ascertained. Because the organic matter in most soils is intimately bound to the clay as a clay-metal-organic complex (Stevenson, 1976), two major types of adsorbing surfaces are normally available to the chemical: clay-organic and clay alone. Clay and organic matter function more as a unit than as separate entities, and the relative contribution of organic and inorganic surface areas to adsorption depends on the extent to which the clay is coated with organic substances. For example, comparative studies between known clay minerals and organic soils suggest that most, but not all, pesticides have a greater affinity for organic surfaces than for mineral surfaces (Stevenson, 1976). Because typical studies compare soils in which both clay and organic matter increase and do not use multiple regression analyses to rank these two properties (Helling, 1970), only generalizations concerning the relative importance of clay and organic surface areas and the clay and organic matter content should be made when empirical data are not available.

Surface acidity is probably the most important property of the soil or colloidal system for determining the extent and nature of adsorption of basic organic chemicals as well as for determining if acid-catalyzed chemical transformation occurs (Baily and White, 1970). Proton activity in bulk suspension, expressed by pH, and proton activity at or proximate to the colloidal surface (i.e., the acidity in the interfacial region) may differ significantly. The term "surface acidity," when applied to soil systems, is the acidity at or near the colloidal surface that reflects the system's ability to act as a Lewis acid (i.e., as an electron pair acceptor). Surface acidity is a composite term that reflects both the total number of acidic sites and their relative degree of acidity.

Available data indicate that the protonation of chemicals in the interfacial region of clays is a function of the basicity of the molecule, nature of the exchangeable cation on the clay, water content of the clay system, and origin of negative charge in the aluminosilicate clay (Baily and White, 1970).

The specific type of interaction that organic molecules have with soil depends on the organic molecules' chemical properties and the type of soil. These interactions or adsorptive forces are hydrophobic bonding (Goring and Hamaker, 1972). In general, one or more of the following specific interactions or adsorptive forces may occur simultaneously.

The van der Waals forces or polarizability forces arise from random fluctuations in a molecule's electron distribution. These fluctuations theoretically produce instantaneous dipoles due to the concentration of charges in one region of the molecule and cause that molecule's attraction to other atoms and molecules.

Charge transfer involves formation of a donor-acceptor complex between an electron donor molecule and an electron acceptor molecule with partial overlap of their respective molecular orbitals and a partial exchange of electron density.

Ion exchange is the exchange between counterions balancing the surface charge of the soil colloid and the ions in the soil solution. The driving force for this interaction is the requirement for electroneutrality: the surface charge must be balanced by an equal quantity of oppositely charged counterions. Ion exchange is reversible, diffusion-controlled, and stoichiometric in most cases. It exhibits some selectivity or preferential adsorption for one ion over another competing ion.

Hydrophobic bonding refers to the greater affinity of an organic molecule for a hydrocarbon solvent or hydrophobic region of a colloid than for a hydrophilic solvent. Hydrocarbon regions of a molecule have greater solubility in liquid hydrocarbons (or most organic solvents) than in water.

The principles governing the mobility and attenuation of organic chemicals in soil systems discussed above were based upon the assumption that water was the primary solvent in the soil system. Because organic chemicals possess different physical and chemical properties than water does, as solvents they can dramatically change soil properties and organic chemical adsorption and reactivity. These changed properties affect the mobility and attenuation of organic chemicals in soils. For example, the presence of organic solvents drastically affected the migration of PCB's at a Superfund site (Erler et al., 1984).

Organic solvents may affect:

- Dispersion/flocculation properties of soil that affect hydraulic conductivity and surface area available for adsorption.

- Shrink/swell properties of soil that affect hydraulic conductivity and surface area available for adsorption.

- Pore-size distribution.

- Dissolution/precipitation of chemical species that can change the proportion of soil volume available for flow.

- Solubility of organic chemicals in soils.

- Rate of organic chemical reactions in soils.

- Relative importance of adsorptive forces between organic chemicals and soils.

Three types of tests have been developed to estimate a chemical's migration potential in soil: soil adsorption tests, soil thin layer chromatography, and soil columns (Hamaker, 1975). Adsorption coefficients (distribution coefficients) are determined in soil adsorption tests. Soil thin-layer chromatography (TLC) is performed to determine soil TLC R_f values, referred to as "retention" or "attenuation" factors. The third test, soil columns, does not develop data that are amenable to standardization and is not utilized as extensively as are the first two tests. Soil adsorption tests and soil TLC tests can be used to determine the transformation rates of organic chemicals; however, they are primarily used to estimate migration potential.

Adsorption coefficients usually are expressed as K_d, the ratio of concentration of organic chemical adsorbed onto soil to its concentration in solution at equilibrium. If K_d has been determined, and if V, groundwater velocity, has been measured during field investigations, then V_c, the velocity of the contaminant front, can be calculated (Dragun et al., 1984) as:

$$V_c = V\,[1 + (b/p)\,(K_d)]^{-1}\ , \qquad (1)$$

where

b is the bulk density of soil, and

p is the soil porosity.

Equation (1) is one of several that mathematically describe a chemical's movement with steady-state flow of groundwater or solvent in a soil and that utilize K_d.

Because the organic matter content of soils is a dominant soil property affecting attenuation of neutral organic chemicals, adsorption coefficients for neutral organic chemicals may be expressed in terms of organic carbon content:

$$K_{oc} = \frac{\mu\text{g chemical adsorbed/g organic carbon}}{\mu\text{g chemical/g water}}\ , \qquad (2)$$

and

$$K_{oc} = \frac{K_d \times 100}{\%\ \text{organic carbon}}\ . \qquad (3)$$

It is possible to reduce the variation in sorption coefficients between different soils (Lyman et al., 1982; Reinbold et al., 1979) with the adsorption coefficient based on percent organic carbon in the soil. The remainder may be attributable to clay content, surface area, cation exchange capacity, and nature of organic matter present. Numerous studies have found that organic carbon content usually gives the most significant correlation (Lyman et al., 1982). For certain chemicals, however, organic carbon content may be of secondary importance in adsorption. An example of one such chemical is benzidine.

Soil TLC is analogous to conventional TLC, with the use of soil instead of silica gels, oxides, etc., as the adsorbent phase. The soil TLC R_f value is the farthest distance traveled by a chemical on a thin-layer chromatographic plate divided by the distance traveled by a solvent front (arbitrarily set at 10.0 cm in soil TLC studies). R_f values are inversely related to K_d values (Helling and Dragun, 1981).

Adsorption coefficients and soil TLC R_f values can be estimated for many neutral organic chemicals, provided solubility or octanol-water partition coefficient (log P) data are available (Dragun and Helling, 1981; Dragun et al., 1980). Equations relating K_d, K_{oc}, and R_f to solubility or log P assume that (1) hydrophobic bonding, as defined above, is the predominant interaction mechanism between a chemical and a soil; and (2) organic chemical transformations are an insignificant process affecting the chemical's attenuation in a soil-groundwater system.

It is important to consider both K_d (or K_{oc}) and R_f values in order to evaluate the relative attenuation expected for organic chemicals of several classes. Because mobility through soils is a complex process, the adsorption coefficient above may not reliably indicate migration potential. The influence of various functional groups that may be present on an organic molecule is better reflected in the measured R_f value.

Another mechanism for reducing chemical concentration in soil is degradation, whether by microorganisms or chemical constituents of the soil. Biodegradation is largely responsible for the mineralization of organic compounds, that is conversion to inorganic products. Chemical reactions, however, play an important role in primary degradation. Water solubility largely determines the rate at which microorganisms are able to change organic compounds. Rao and Davidson (1982) present extensive data on degradation of pesticides in soils.

Not all degradation products are less toxic or hazardous than the parent species, though this is generally the case.

The chemical reactions that occur in water at standard temperature and pressure also occur in the water phase of soil-groundwater systems. These chemical reactions, in general, are hydrolysis, oxidation, and reduction. These reaction rates for organic chemicals in soil-groundwater systems may differ significantly from those in water alone due to the presence of aluminosilicate minerals in soils (Dragun et al., 1980).

Reaction rates may be reduced if soils are dry. Water, by definition, is required for hydrolysis and is essential for bringing oxidative and reducing elements in contact with organic chemicals.

Crystalline aluminosilicate materials, which catalytically transform organic chemicals, have been used for many years in petroleum refining and in the chemical and petrochemical industries. These catalysts are important in many high-temperature, high-pressure reactions such as ammonia synthesis, conversion of hydrocarbons with water vapor to synthesis gas, dehydrocyclization, the Fischer-Tropsch synthesis, isomerization of paraffins and cycloalkanes, hydroisomerization of olefins and dienes and aromatics, isomerization of ethyl benzene to xylenes, oxidation, and reduction (Dragun et al., 1980). Soils also contain aluminosilicate materials; the ability of clay soils to catalyze the chemical oxidation, reduction, and hydrolysis of organic chemicals at ambient pressure and temperature has been recognized (Dragun and Helling, 1982; Theng, 1974). These reactions are gaining more attention because the susceptibility of organic chemicals to accelerated degradation and decreased persistence may result in increased agricultural use or in diminished concern over their potential hazard to human health and the environment.

Microorganisms are the most significant group involved in biodegradation, although higher organisms--both plant and animal--can metabolize numerous compounds. Furthermore, microorganisms may be the first agents in biodegradation, converting compounds into the simpler forms required by higher organisms.

For any one microorganism, organic compounds can be divided into four groups according to their biodegradability: (1) usable immediately as an energy or nutrient source, (2) usable following acclimation by microorganisms, (3) degraded slowly or not at all, and (4) subject to cometabolic degradation. A chemical may be classified in more than one category, depending on the response of the microorganisms to which it is exposed. Different species may react differently to the same compound.

The second group requires acclimation, a lag period with little or no degradation. Lag periods vary from a few hours to days or even weeks, depending on the chemical, the organism, and the medium. Once acclimation is achieved, the degradation reaction begins. Intensive activity occurs first with primary alteration of the introduced substance, usually followed by slower activity as the intermediate products are digested. The microbial population increases at first, levels off, and declines once the substrate has disappeared or has been converted either to nonmetabolizable catabolites or to inorganic compounds. The disappearance curve for the parent compound can follow one of several forms, depending upon the kinetics of the reaction.

The third group of organic compounds includes such naturally occurring substances as humus and lignin, as well as such anthropogenic substances as some of the organochlorine pesticides. These substances degrade at very slow rates or not at all. Furthermore, they may not be degradable due to factors such as physical inaccessibility or environmental influences (low O_2, pH, etc.).

The fourth group involves cometabolism: the degradation of a compound that does not provide a nutrient or energy source for the degrading organisms but is broken down during the degradation of other substances. Because cometabolism does not provide a growth substrate, the population increase characteristic of metabolic degradation reactions does not occur and the degradation rate is often slower. Compounds with chlorine, nitro, or other substituents are sometimes susceptible to cometabolism. Soil perfusion, soil incubation, and soil suspended in aqueous solution are three methods used to test for degradation in soils.

TSCA recommends the soil incubation test in which the CO_2 that is evolved is measured (Lyman et al., 1982).

Two general rate laws are used to describe biodegradation: the power rate law, and the hyperbolic rate law. These simplified models may not fully describe the concentration change over time because of altered concentration-dependency and availability over time. Application of the rate equation depends on factors such as cometabolism, adsorption strength, and simultaneous competing reactions.

The power rate law states that the change in concentration per unit time is proportional to the substrate concentration raised to some power:

$$\frac{dC}{dt} = K\,C^{n}\ , \qquad (4)$$

where

C = concentration of substrate,

K = biodegradation rate constant, and

n = order of the reaction.

A first-order reaction (n = 1) is commonly assumed and is used to calculate the biodegradation half-life ($t_{\frac{1}{2}}$). The $t_{\frac{1}{2}}$ is equal to 0.693/K. A chemical's half-life is one of the more readily available parameters. At low concentration, the first-order rate equation is a reasonable assumption.

The hyperbolic rate law is based on microbial population growth and is useful for dealing with mixed microbial populations. A simplified form of the equation is:

$$\frac{-dC}{dt} = KBC\ , \qquad (5)$$

where

B = the microbial population concentration, and •

the equation is a second-order rate expression.

These equations may well predict biodegradation under laboratory conditions. Extrapolation to the field must be done with care. Estimating biodegradation rates, when no laboratory or field studies are available, is best done with known structural factors and chemical class and on a qualitative basis. Quantification is difficult because an adequate data base does not exist. Several estimation techniques have been proposed but are not recommended (Lyman et al., 1982).

The lack of quantitative biodegradation data does not reflect the importance of biodegradation to the attenuation of chemicals in soil. Top soils are microbe-rich and have the highest organic contents. The upper layer of soil, which is the source of fugitive emissions, is the most dynamic in terms of adsorption and biodegradation. The nature of soil-chemical interaction must be evaluated both empirically and theoretically to address the potential hazards of hazardous waste sites.

4.2 TYPES OF SOIL CONTAMINATION

Types of contamination can be categorized by various characteristics including properties of the contaminant and nature of the contaminating process.

Typical contaminants are hazardous organic compounds (liquid or solid), heavy metals, radioactive compounds, and some inorganic compounds. Of major interest are hazardous organic compounds that already exist as dusts or that have the potential for adsorbing onto erodible soil particles. Compounds with high viscosity and/or surface tension are expected to be less troublesome because of their ability to hold soil particles together and prevent erosion or mechanical separation.

Contamination may result from such actions as accidental spills, long-term storage, seepage and leakage from containers, and discharges from vehicles or machinery. In each process the contaminant, when a liquid, is in contact with a body of soil for sufficient time to allow near-equilibrium adsorption (on the order of 1 to 2 days). Erosion of dry soil particles can then occur. Shorter times that keep the soil wet or tacky will prevent wind erosion under normal conditions.

4.3 DEGREE OF SOIL CONTAMINATION

For a given waste site, degree of contamination (DOC) depends on combined results of the soil-chemical interactions discussed in Section 4.1. The primary retention process for unconfined organic substances is adsorption onto soil particles. Although many mechanisms may be involved in the process, the Freundlich adsorption equation can be used to correlate surface concentration of an adsorbate with solution concentration at equilibrium. For soils, the process can be visualized as a partitioning of the adsorbate between moisture and organic material in the soil. The adsorbate generally adsorbs rapidly onto the surface of the soil but then may migrate to the interior of the soil particles over weeks or months. This behavior may lead to permanent binding of the adsorbate to the soil. The adsorption characteristics for organic compounds can be measured to calculate adsorption coefficients that are unique to a particular chemical/soil combination.

When measurements are not available, estimation methods based on chemical properties can be used.

Lyman (1981) has compiled methods to estimate adsorption coefficients for soils and sediments. Of particular interest is K_{oc}, introduced earlier in slightly different form, a coefficient based on the soil's organic carbon content and an adsorbing chemical's concentration in water solution:

$$K_{oc} = \frac{\mu g \text{ adsorbed/g organic carbon}}{\mu g/mL \text{ solution}} . \qquad (6)$$

The coefficient also can be developed from the Freundlich adsorption isotherm equation:

$$x/m = K\,C^{1/n} , \qquad (7)$$

where

x = amount of chemical adsorbed on soil, μg.
m = mass of adsorbent, g.
K = Freundlich adsorption coefficient, (μg/g)/(μg/mL).
C = concentration of chemical in solution at equilibrium, μg/mL.
n = curve-fitting value generally ranging from 0.7 to 1.1.

After adsorption-isotherm experiments have been performed and the data fitted to equation (7), values for K_{oc} can be obtained from:

$$K_{oc} = (K/\text{percent oc}) \times 100 , \qquad (8)$$

where

oc = organic carbon in the soil.

Values for K_{oc} are relatively independent of soil properties other than organic carbon.

Based on equations (8) and (7), a value for the amount of chemical adsorbed (DOC) can be calculated if K_{oc}, C, and n are known. Values for K_{oc} can be estimated, while those for n must be measured or found in the literature. Lyman (1981) reports that no estimation methods for n are available. Values for C, the chemical concentration in solution when the solution is in equilibrium with surrounding soil, depend on the adsorption process. They generally will not be known. An upper bound, however, can be obtained from the solubility, S, of the chemical in water if it is assumed that C cannot exceed S. Another implicit assumption is that the chemical is not acting as an infinite source to replenish solution concentration as it is depleted or alternatively that all adsorption sites are filled by single contact with the saturated solution. Replacing C with S and K with (K_{oc}) (percent oc)/100 gives:

$$x/m = d = (K_{oc})(\text{percent oc})(S)^{1/n}/100 \;, \tag{9}$$

where

d = degree of contamination.

If C_o = fractional organic carbon, equation (4) becomes:

$$d = (K_{oc})(C_o)(S)^{1/n} \;. \tag{10}$$

If measured values of K_{oc} are not available, the coefficient can be estimated from equations collected by Lyman (1981). He tabulates the 12 regression equations presented in Table 4. Besides water solubility as a correlating factor, Table 4 gives octanol-water partition coefficient (K_{ow}), bioconcentration factor, and parachor (a function of molecular weight, surface tension, and liquid and vapor densities). If any of these parameters is known for the chemical of interest, K_{oc} can be estimated through the appropriate equation. Tables of K_{oc}, or K_{ow}, and water solubility are given in Appendix B for a variety of chemicals. Rao and Davidson (1982) give extensive tables of K_{oc}, K_{ow}, other adsorption data, and some information on apparent half-lives of many pesticides. Lyman, Rheel, and Rosenblatt (1981) describe estimation methods for solubility and octanol-water partition coefficient if no measured or tabulated values are available.

Because solubility is temperature dependent, values of K_{oc} calculated from the correlating equations will be most nearly correct only for the temperature at which solubility is measured. A further confounding factor is the tendency for some organic chemicals to become more soluble as temperature increases, while others become less so.

Lyman (1981) and Hamaker and Thompson (1972) list K_{oc} values for many soil/chemical combinations and provide examples of adsorption calculations. Hamaker and Thompson suggest that the value of $1/n$ in equation (7) is 1 for many cases of adsorption on soils but that the choice may be for convenience as much as for accuracy. Their data show values ranging from about 0.7 to 1.0. With $1/n$ equal to 1, the Freundlich equation becomes linearly proportional to solution concentration. Hamaker and Thompson discuss the errors associated with choosing the wrong value for $1/n$.

For some soils, percentage of organic matter rather than of organic carbon is reported. Different authors use different conversion factors to obtain percentage organic carbon, but a common value is 1.724. For soils of high organic carbon content (greater than about 8.7 percent), measured values of K_{oc} tend to be lower than for soils of lower carbon content. This effect may be due to the reduction in available adsorption sites as organic matter becomes less dispersed in the soil (Hamaker and Thompson, 1972). Rao and Davidson (1982) list properties for many soils along with values of K_{oc}.

TABLE 4. REGRESSION EQUATIONS FOR THE ESTIMATION OF K_{oc} (Lyman, 1981)

Eq. no.	Equation[a]	No.[b]	r^2[c]	Chemical classes represented
29	$\log K_{oc} = -0.55 \log S + 3.64$ (S in mg/L)	106	0.71	Wide variety, mostly pesticides
30	$\log K_{oc} = -0.54 \log S + 0.44$ (S in mole fraction)	10	0.94	Mostly aromatic or polynuclear aromatics, two chlorinated
31[d]	$\log K_{oc} = -0.557 \log S + 4.277$ (S in μ moles/L)	15	0.99	Chlorinated hydrocarbons
32	$\log K_{oc} = 0.544 \log K_{ow} + 1.377$	45	0.74	Wide variety, mostly pesticides
33	$\log K_{oc} = 0.937 \log K_{ow} -0.006$	19	0.95	Aromatics, polynuclear aromatics, triazines, and dinitroaniline herbicides
34	$\log K_{oc} = 1.00 \log K_{ow} -0.21$	10	1.00	Mostly aromatic or polynuclear aromatics, two chlorinated
35	$\log K_{oc} = 0.94 \log K_{ow} + 0.02$	9	e	s-Triazines and dinitroaniline herbicides
36	$\log K_{oc} = 1.029 \log K_{ow} -0.18$	13	0.91	Variety of insecticides, herbicides, and fungicides
37[d]	$\log K_{oc} = 0.524 \log K_{ow} + 0.855$	30	0.84	Substituted phenylureas and alkyl N phenylcarbamates
38[d,f]	$\log K_{oc} = 0.0067 (P - 45N) + 0.237$	29	0.69	Aromatic compounds: ureas, 1,3,5-triazines, carbamates, and uracils
34	$\log K_{oc} = 0.681 \log BCF(f) + 1.963$	13	0.76	Wide variety, mostly pesticides
40	$\log K_{oc} = 0.681 \log BCF(t) + 1.886$	22	0.83	Wide variety, mostly pesticides

---

[a] K_{oc} = soil (or sediment) adsorption coefficient; S = water solubility; K_{ow} = octanol water partition coefficient; BCF(f) = bioconcentration factor from flowing water tests; BCF(n) = bioconcentration factor from model ecosystems; P = parachor, N = number of sites in molecule that can participate in the formation of a hydrogen bond.

[b] No. = number of chemicals used to obtain regression equation.

[c] r^2 = correlation coefficient for regression equation.

[d] Equation originally given in terms of K_{om}. The relationship $K_{om} = K_{oc} 1.724$ was used to rewrite the equation in terms of K_{oc}.

[e] Not available.

[f] Specific chemicals used to obtain regression equation not specified.

TABLE 4 (continued) References

Eq. no.	References
29	Kenaga and Goring (1978)
30	Karickhoff, Brown, and Scott (1979)
31	Chio, Peters, and Freed (1979)
32	Kenaga and Goring (1978)
33	Brown, Karickhoff, and Flagg (1981)
34	Karickhoff, Brown, and Scott (1979)
35	Brown (1979)
36	Rao and Davidson (1982)
37	Briggs (1973)
38	Hance (1969)
39	Kenaga and Goring (1978)
40	Kenaga and Goring (1978)

As a guideline for the amount of adsorption taking place, Hamaker and Thompson state that for adsorbates with sorption constants greater than unity, most of the chemical is adsorbed in soils with normal moisture contents. This behavior explains the resistance to leaching shown by many chemicals that remain in upper layers of soil longer than expected based on their solubilities. The sorption constant used by Hamaker and Thompson is:

$$K_d = (K_{oc})(\text{fraction of organic carbon}) \ . \qquad (11)$$

DOC for a given soil type can be estimated similarly to the following example. Assume a silty soil estimated to contain 2.43 percent organic carbon is contaminated with DDT having a solubility in water, at ambient temperature, of 0.0017 μg/mL. Goring (1972) lists a DDT value for K_{oc} of 1.31×10^5. With these values, and assuming that 1/n in equation (7) is 1, DOC (at saturation) is:

$$\begin{aligned} d &= (K_{oc})(C_o)(s) \\ &= (1.31 \times 10^5)(0.0243)(0.0017) \qquad (12) \\ &= 5.41 \ \mu\text{g DDT/g soil} \ . \end{aligned}$$

For equilibrium solution concentrations less than saturation, DOC would be reduced accordingly and could be calculated from equation (7).

The preceding estimation method assumes no degradation processes reduce the soil's DDT content over time or that contamination is of recent origin. For the case of degradation over extended time, one can assume a first-order decay mechanism as discussed in Section 4.1. Sleicher and Hopcraft (1984) found half-lives for DDT of 110 and 160 days for an exposed plot and a shaded plot. If the 160-day value is assumed for our example and the DDT is assumed to have been in the soil for 2 years, DOC at that time can be calculated from:

$$d = d_o \exp(-0.693/t')t \ , \qquad (13)$$

where

d_o = degree of contamination at time zero, μg/g.
t' = half-life, days.
t = time since contamination, days.

For the example:

$$\begin{aligned} d &= 2.05 \ [(-0.693/160)(730)] \qquad (14) \\ &= 0.089 \ \mu\text{g DDT/g soil.} \end{aligned}$$

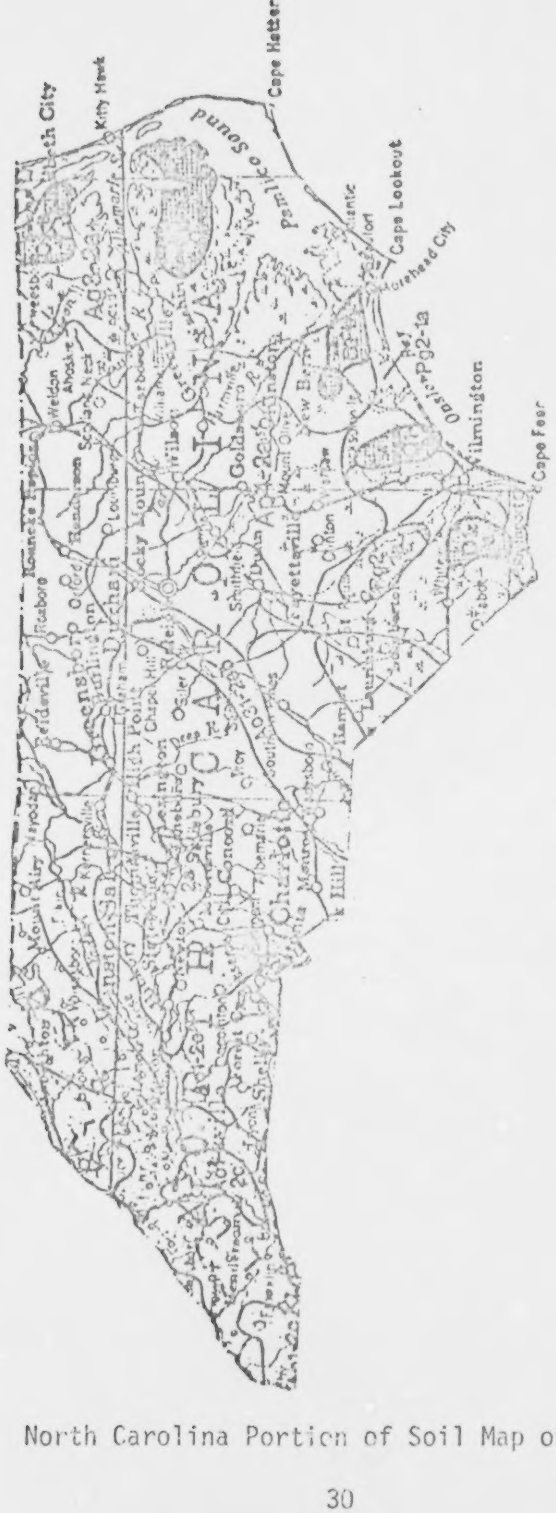

Cape Hatteras
Kitty Hawk
Pamlico Sound
Cape Lookout
Morehead City
Wilmington
Cape Fear
Goldsboro
Fayetteville
Durham
Charlotte

Figure 5. North Carolina Portion of Soil Map of the World. (UNESCO, 1975)

If half-life data are not available, but a chemical's concentrations are known at two different times, the first-order half-life can be found from:

$$t' = (\ln 2)/k = 0.693/k, \text{ and} \tag{15}$$

$$k = (\ln C_o - \ln C)/t , \tag{16}$$

where

C_o = concentration at time zero.
C = concentration at any time, t.
k = rate constant.

If the soil's carbon content is not known, the FAO/UNESCO soil map of the world may be used for a rough estimate. The map for North America is divided into units based on soil texture and slope classes. Symbols and colors are used to differentiate between various soil classes. A small section of the map, the State of North Carolina, is illustrated in Figure 5. This map is divided into various regions based on soil type. Some of the symbols encountered within the State of North Carolina include:

- Ao31-2ab
- Ap4-2a
- O1-a
- Ag3-2a
- Ao1-2c

Symbols preceding the dash (-) correspond to a dominant soil unit. A complete description of the various soil units including such information as percent sand, silt and clay, pH, organic carbon content, and moisture content is located in the text that accompanies the map. The number following the dash indicates the soil texture; coarse, medium, and fine are represented by the numbers 1, 2, and 3, respectively. The lower case letter following the dash indicates the slope. Level to gently undulating, rolling to hilly, and strongly dissected to mountainous are represented by the letters a, b, and c, respectively.

An example of site-specific information variability from the soil map is illustrated by the case study of PCB contamination along North Carolina roadsides. Meyer (1984) indicates that the organic carbon content of contaminated soil along roadsides in Johnston County, North Carolina, ranged from 5 to 10 percent. This location in Figure 5 shows both Ao31-2ab and Ap4-2a soil units. The corresponding soil types are:

Soil type	Organic carbon, %
Ferric acrisol	0.24
Gleyic acrisol	2.50
Orthic acrisol	2.92

The organic carbon content of these soils, as the soil map indicates, is less than the value obtained for the specific soil of interest.

SECTION 5
ESTIMATION OF FUGITIVE PARTICULATE EMISSION RATES

The ideal method for estimating fugitive particulate emission rates from a hazardous waste facility is to measure emissions under different operational and climatic conditions at a given hazardous waste site/facility. Because few such data are available, estimates must be made by extrapolation of data from other facilities. Differences between the hazardous waste facility considered and the source where the data are being adapted, must be considered, the most important likely to be soil and surface characteristics, which are also difficult to predict. Measurements from a given facility are likely to produce emission estimates accurate within only an order of magnitude. Because of uncertainties involved in several factors, extrapolation of available data from other sources could be in substantial error.

For an extrapolation of existing data, the characteristics and influencing factors at a hazardous waste facility must be identified and defined clearly and a search made for a site similar to the facility considered. Differences between the two sites must be determined and quantified. Finally, based on these differences, modifying factors should be formulated to adapt existing source data to the case considered.

Most available fugitive particulate emission data concern respirable and total particulate emissions with little reference to complete particulate size distribution and contaminant concentrations. As a first approximation, it may be assumed that the contaminant species is distributed uniformly throughout the soil particles and has a constant mass concentration irrespective of particle size.

5.1 AVAILABLE APPLICABLE DATA

Available data applicable for simulating hazardous waste facilities may be grouped into three broad categories:

- Wind erosion and resuspension of particles from open fields that may be able to simulate fugitive emissions from capped and uncapped landfills, dried lagoons and ponds, and open drum storage facilities.

- Data from aggregate storage piles and coal piles that may be able to simulate fugitive emissions from open waste piles.

- Data obtained from unpaved roads and haul roads that may be useful to simulate emissions from a contaminated road.

A good review of the soil erosion and particle resuspension models is given by Dynamac Corporation (1983) and Smith et al. (1982).

Details of the wind erosion equation are given by Woodruff and Siddoway (1965). This equation considers 11 primary variables grouped in 5 parameters and includes all soil characteristics and wind velocity. Its drawback is that it estimates net soil loss with no information regarding respirable or suspended particle emissions. The fraction of suspended particles also must be determined to predict fugitive emissions with this equation. Sehmel (1980) determined that 3 to 40 percent by weight of total soil particle loss may be attributed to suspension, 50 to 75 percent to saltation, and 5 to 25 to surface creep. Thus, in theory this equation can be used to obtain at least an order of magnitude estimate of fugitive emissions from open field sources.

The wind erosion equation was used by Jutze and Axetell (1974) to predict emissions from a flat, dried tailings pile. Due to the fine nature of the surface particles involved, about 10 percent of the soil loss predicted by the equation was attributed to suspension. Thus, such an approach may be used to determine fugitive emissions from open sources and is suggested by PEDCo (1977), Versar (1983), and U.S. Environmental Protection Agency (EPA) (1977) Publication Office of Air Quality Planning and Standards (OAQPS) No. 1.2-071.

Research on particle suspension by wind attempts to correlate vertical flux (suspension) and horizontal flux (saltation) with the wind velocity profile and the threshold drag or friction velocity. Bagnold (1941), for example, correlated the saltation flux with wind velocity by the following correlation:

$$F_h = C\ (d/D)^{\frac{1}{2}}\ (p/g)\ U_*'^{3}\ , \tag{17}$$

where

F_h = saltation flux (mass/time/crosswind length).

D = reference grain diameter of 250 μm.

C = an empirical constant equal to 2.8 for sand.

d = grain diameter.

g = gravitational acceleration.

p = grain density.

U_*' = friction velocity during erosion.

The saltation flux can be multiplied by a proportional constant, k, to further obtain desired vertical suspension flux. Mills et al. (1974) determined the proportionality constant to be 10^{-10} (/m) from the data of Gillette et al. (1972). Gillette and his coworkers (Gillette et al., 1972; Gillette, 1974a; Gillette, 1974b) studied size distribution and vertical suspension. Based on his data, Gillette (1974b) related suspension flux by the following correlation:

$$F_v = C\ (U'_*/U_{*t})^\gamma\ , \tag{18}$$

where

F_v = suspension flux (mass/area/time).
C = a constant.
U'_* = drag velocity measured during wind erosion.
U_{*t} = the threshold drag velocity.

The constant γ is highly site-specific and is greater than 3.

The above correlations are specific to the type of soil studied in those experiments. To use the flux correlations, one must know the friction velocity for the specific site of interest, which is a strong function of the soil's particle size distribution and type. Also, climatic factors such as the soil's moisture content must be taken into account. The above experiments were conducted with soils having continuous erosion potential so the presence of nonerodible elements such as large rocks or stones also must be considered.

In addition to research determining the flux of particles due to wind erosion, several researchers studied the resuspension factor, which is the ratio of airborne contaminant concentration to surface contaminant concentration (Sehmel, 1980). However, this factor does not give any information regarding the rate at which contaminants are emitted and therefore is not readily applicable (Dynamac, 1983). When multiplied by the resuspension rate, surface concentration can give a usable emission rate; however, measurements of this rate show several orders of magnitude variations (Sehmel, 1980). Resuspension rates depend upon several factors such as surface characteristics, windspeed, and type of contaminant; further research is needed to characterize resuspension rates for various influencing parameters.

Recently, Cowherd et al. (1984) recommended a methodology for rapid assessment of exposure to particulate emissions from surface contamination sites. To estimate fugitive emissions due to wind erosion, they suggested two different equations based on erodibility of soil surface. Soils and surface material with a friction velocity less than 75 cm/s were considered to have unlimited erosion potential, whereas those having the friction velocity greater than 75 cm/s were considered to have limited erosion potential. The friction velocity of 75 cm/s corresponds to an ambient windspeed of about 10 m/s (22 mph), measured at a height of about 7 m. The threshold friction velocity depends upon soil particle size distribution, large roughness elements not included in size distribution, soil crusting, and surface roughness height. Methods to estimate friction velocity by considering the above factors are also included in this report.

For surfaces with unlimited erosion potential, which are characterized by bare loose fine soil, a horizontal saltation-type equation was suggested by Cowherd et al. (1984) as shown below:

$$E_{10} = A\ (1 - V)\ u^3\ F(x)\ , \tag{19}$$

where

E_{10} = PM_{10} emission factor, i.e., annual average PM_{10} emission rate [g/m^2-hr)], (particles smaller than 10 μm).

A = constant determined from Gillette's dust flux measurements and equals 10^{-13} $g\text{-}s^2/cm^5$.

V = fraction of contaminated surface vegetative cover.

u = mean annual windspeed (m/s).

x = a dimensionless ratio and equals 0.886 u_t/u.

F(x) = a function of x as given by Cowherd et al. (1984).

This equation is applicable to highly erodible soils that do not retain significant moisture. Therefore, no moisture-related climatic parameter is included in this equation.

For surfaces characterized by a limited reservoir of erodible material, the half-life of the erosion process is of the order of minutes and the threshold friction velocity is greater. Therefore, wind gusts reduce erosion potential. Erosion potential, although limited, may again be restored due to a disturbance that exposes fresh erodible surface material. Such a disturbance occurs whenever aggregate material is either added or removed from the old surface. The emission rates thus would depend on frequency of disturbances. Cowherd et al. (1984) recommended the following equation for surfaces with limited erosion potential:

$$E_{10} = 0.83\ \frac{f\ P(u^+)\ (1 - v)}{(P\text{-}E/50)^2}, \tag{20}$$

where

E_{10} = PM_{10} emission factor [mg/m^2-hr)].

f = frequency of disturbance per month.

u^+ = observed or probable fastest mile of wind for the period between disturbances.

$P(u^+)$ = erosion potential, i.e., quantity of erodible particles present on the surface prior to the onset of wind erosion.

v = fraction of contaminated surface area covered by continuous vegetative cover.

P-E = Thornthwaite's precipitation-evaporation index used to measure average soil moisture content.

For a coarse aggregate material (e.g., coal with a top size of 3 cm and a silt content >4 percent), erosion potential $P(u^+)$ is related to the fastest mile as follows:

$$P(u^+) = 3\ (u^+ - u_t) \quad \text{for } u^+ \geq u_t$$
$$= 0 \quad \text{for } u^+ < u_t\ , \qquad (21)$$

where

u_t = threshold speed for the onset of wind erosion.

Thornthwaite's P-E index can be obtained from

$$PE = 10 \times \sum_{i=1}^{12} \{11.5 \times [P_i/(T_i - 10)]10/9\}\ , \qquad (22)$$

where

P_i = total monthly precipitation, in. of rain.

T_i = mean monthly temperature, °F, $\geq$28.4.

If the term within braces is greater than 40 for any month, 40 is used.

Data obtained from aggregate gravel and coal storage piles may be used to estimate fugitive emissions from abandoned waste piles. In contrast to storage piles in mining and iron industries, where storage piles are "active" due to frequent loading and unloading operations, the waste piles are relatively inactive with wind erosion as the dominant mechanism for emissions. The emission rate depends upon aggregate size distribution, moisture content, and windspeed. The emission rate from a pile also may be expected to be time-dependent, with a maximum at the initial onset of erosion and a rapid decline with time. Erosion potential is maximum after a fresh loading of material and may be restored later after a disturbance. The erosion potential also depends upon the fastest mile windspeed between disturbances (Cowherd, 1983).

Cowherd et al. (1974) studied the fugitive particulate emission rate from aggregate sand and gravel piles. The empirical emission factor attributed to wind erosion, derived from these data after application of a climatic correction factor, is:

$$E = 0.11/(PE/100)^2\ , \qquad (23)$$

where

E is the emission factor (lb/ton of material in storage).

This factor has been included in EPA publication AP-42, supplements 1 to 12 (EPA, 1981), a document containing recognized emission factors for many sources. This factor also may be converted to rate by changing the coefficient to 3.5 (PEDCo, 1977); the emission rate would then be in "lb/acre of storage/day." This emission factor may be more applicable by introducing the correction factor for silt content and duration of storage of material. Such an equation as given by PEDCo (1977) is:

$$E = \frac{0.11\ (s/1.5)}{(PE/100)^2}\ \frac{D}{90}\ , \qquad (24)$$

where

s = percent silt content of aggregate material.

D = duration of material in storage.

Bohn et al. (1978) investigated fugitive emissions from the iron and steel industry, which included wind erosion emissions from coal storage piles. The empirically derived emission factor is:

$$E = 0.05\ (s/1.5)\ (d/235)\ (f/15)\ (D/90)\ , \qquad (25)$$

where

E = emission factor (lb/ton of material in storage);

d = number of dry days per year (rainfall <0.01 in.);

f = percentage of time windspeed exceeds 12 mph at 1 ft above ground.

The above emission factor may be converted to an emission rate by changing the coefficient to 1.7 and omitting the D term (Cowherd et al., 1984). The emission rate would then be "lb/acre of storage/day." This equation does not have the P-E index term but instead considers number of dry days.

Recently, Cowherd (1983) studied emissions from a coal storage pile considering the erosion potential approach. The resulting emission rate was:

$$E = 720\ f\ P(u_{15}^{+})\ , \qquad (26)$$

where

E = emission rate expressed as g/m^2-h.

f = frequency of disturbance.

$P(u_{15}^{+})$ = erosion potential corresponding to the observed fastest mile of wind between disturbances, after the fastest mile was corrected to a height of 15 cm (g/m^2).

Erosion potentials for various surfaces and different windspeeds also were reported.

Blackwood and Wachter (1978) also studied fugitive emissions from a coal storage pile and arrived at the following empirical correlation:

$$E = 336 \frac{u^3 \, p_b^2 \, A^{0.345}}{(P-E)^2} , \qquad (27)$$

where

E = emission rate, mg/s.

u = windspeed, m/s.

p_b = coal density, g/m².

A = surface area, m².

Emissions from unpaved roads are dominated by vehicular activity rather than by wind erosion. Vehicle speed, weight, number of wheels per vehicle, moisture content, and silt content of the soil influence the emission rate. The emission factor usually is expressed as emissions per unit vehicle mile traveled (VMT).

Cowherd et al. (1974) investigated vehicular emissions from unpaved roads and empirically fit the data by the following correlation:

$$E = 0.81 \, s(S/30) , \qquad (28)$$

where

E = emission factor, lb/VMT for total particulates.

s = silt content of road material, fraction.

S = average vehicle speed mph.

Emissions were negligible for wet days having rainfall greater than 0.01 in., and about 60 percent of total particles were below 30 μm. This equation was subsequently adopted in EPA Document AP-42 (1981). It does not consider the effect of vehicle weight or number of wheels per vehicle. These factors were included in the recent report by Cowherd et al. (1984), who recommended the following equation to estimate emissions of particles in the inhalable range (particles smaller than 10 μm):

$$E_{10} = 0.85 \, (s/10)(S/24)^{0.8} \, (W/7)^{0.3} \, (w/6)^{1.6} \, (d/365) , \qquad (29)$$

where

E_{10} = PM_{10} emission factor for a vehicle kilometer traveled, kg/VKT.

W = mean vehicle weight, Mg.

w = mean number of wheels per vehicle.

Studies by Dyck and Stukel (1976) indicate the importance of including vehicle weight and wheel parameters in the prediction equation. They suggested the following equation:

$$E = 5.286 - 3.599R + 0.00271\ S\ W\ s\ , \qquad (30)$$

where

E = emissions, lb/VMT.

R = road surface type: USCS: SM = 1, CL = 0, dimensionless.

S = vehicle speed, mph.

W = weight in thousands of pounds.

s = percent silt content.

Bohn et al. (1978) studied fugitive emissions from unpaved roads in the iron and steel industry areas and derived the following empirical relationships:

$$E = 5.9\ (s/12)\ (S/30)\ (W/3)^{0.7}\ (w/4)^{0.5}\ (d/365)\ , \qquad (31)$$

where

E is an emission factor, lb/VMT.

Axetell and Cowherd (1981) studied fugitive emissions from Western surface coal mining sources. Relationships obtained for emissions due to haul trucks and due to light- and medium-duty vehicles are given below. Separate correlations were obtained for total suspended particulates (TSP) and inhalable particulates (IP). For haul trucks:

$$E = 0.0067\ w^{3.4}\ s^{0.2}\ \text{(TSP), and} \qquad (32)$$

$$E = 0.0051\ w^{3.5}\ \text{(IP)}\ ; \qquad (33)$$

for light- and medium-duty vehicles:

$$E = 5.79/M^{4.0}\ \text{(TSP), and} \qquad (34)$$

$$E = 322/M^{4.3}\ \text{(IP)}\ , \qquad (35)$$

where

E = emission factor, lb/VMT.

M = soil moisture content, percent.

w = average number of wheels per vehicle.

s = silt loading, gm/m^2.

5.2 DATA REQUIRED TO SIMULATE SITE DESIGN CHARACTERISTICS

Fugitive particulate emissions from contaminated roads, open waste piles, dried lagoons, drum storage facilities, and uncapped landfills are estimated for use as input to currently available dispersion models such as the industrial source complex (ISC) model. The contaminated road is represented by a line source, the open waste pile is represented by a storage pile model, and the remaining three types of facilities are assumed to be point or area sources.

Information necessary for the line source model includes:

- Soil type (percent clay, silt, and sand)
- P-E index
- Average wind velocity
- Level of mechanical activity on the road.

In many cases, values for the first three parameters may be available from the literature or through government agencies such as the U.S. Department of Agriculture (USDA). Values for the level of mechanical activity and resulting emissions along contaminated roads are reported in many publications. Examples are Dyck and Stukel (1976), Roberts et al. (1975), and Rosbury and Zimmer (1983). Emission factors are given in AP-42 (EPA, 1981) and its supplements.

Data required for particulate emission from a storage pile are:

- Wind velocity
- Activity at the waste pile
- Particle size(s) of the waste material
- Water or moisture content of the waste
- Dimensions of the waste pile.

Values for the last three parameters may have to be estimated.

The point or area source emission model used to estimate emissions from the remaining types of facilities requires the following data:

- Wind velocity
- Soil type (percent clay, silt, and sand)
- P-E index
- Typical dimensions
- Soil ridge roughness.

Values for the first four parameters are obtained as previously discussed. A value for soil ridge roughness, the natural or artificial roughness of the soil surface due to ridges is estimated.

5.3 SITE DESIGN CHARACTERISTICS

The types of facilities discussed as possible sources of fugitive particulate emissions (contaminated roadsides, open waste piles, dried lagoons, drum storage facilities, and soil-capped landfills) have been introduced previously. Generalized descriptions of facility types are discussed below, with a specific example of each and its soil characteristics and contamination. Example sites are described more fully by degree of contamination (DOC), meteorology, control, and emissions in appropriate parts of the report or its appendixes.

Contaminated roads may result from leaky transporting equipment or from "midnight dumpers." In both cases, potential for contaminants to enter surrounding soils is great, especially when the source of contamination goes unnoticed for an extended time. The nature of these roads and roadsides (unpaved soils usually with limited vegetation), makes them susceptible to mechanical or wind erosion, which may subsequently cause downwind contamination.

An example was the illegal dumping of PCB's that occurred along approximately 240 miles of rural North Carolina roadsides during the summer of 1978 and that contaminated 40,000 yd^3 of soil (Aroclor, 1260). The average contamination level was 125 ppm (Meyer, 1982). The types of soil contaminated (Meyer, 1984) were 15 to 20 percent clay, 30 to 45 percent silt, 40 to 50 percent sand, and 5 to 10 percent organic carbon.

The relatively large percentage of organic carbon in the soils indicates that the PCB's will adsorb readily onto the soil particles and that, in some areas, there may be more than just a limited vegetative cover. However, for example purposes discussed later, the existence of a 1-km open section of unvegetative contaminated road was assumed whose soil contained 7 percent organic carbon, 20 percent clay (<0.002 mm), and 35 percent silt (0.002-0.05 mm).

Open waste piles are a potentially large source of fugitive particulate emissions whose fine material can easily be eroded by wind; precipitation can cause contaminated runoff, which in turn can pollute local soils. These soils may then cause downwind contamination if they are eroded. Roberts and Johnson (1978) describe spoil heaps at an abandoned mine complex in Minera, Wales, that have led to extensive metal contamination of surrounding surface soils. Between 1761 and 1909, when the facility was active, mineral ores were excavated, subjected to a preliminary mineral segregation process, and refined. The waste materials, fine-grained spoils (<2 mm), were discarded in a central area either as conical tips or as tailings deposited in lagoons. These disposal practices, common for early mining operations, produced unstable matrices susceptible to reentrainment by wind and surface drainage (Johnson and Bradshaw, 1977). Erosion is also encouraged by disturbances of the spoil tips through recreational activities and small-scale reprocessing ventures. Recently, a study of surrounding areas indicated high levels of lead and zinc contamination. Lead and zinc concentrations were found to decrease exponentially with distance downwind of the spoil heaps. This dispersal of metal-rich waste materials has been attributed to many factors including wind erosion (Roberts and Johnson, 1978).

Approximately 340 soil samples were taken from the area surrounding the abandoned site, and the lead and zinc concentrations were determined. These values declined from roughly 5,000 µg Pb/g and 11,000 µg Zn/g close to the waste materials, to background levels of 95 µg Pb/g and 150 µg Zn/g within 600 and 750 meters respectively (Roberts and Johnson, 1978). The lead and zinc concentrations of the waste pile material was highly variable. Average lead concentrations were 14,000 ppm, and average zinc concentrations were 34,000 ppm.

Low-permeability soils often are used to line hazardous waste lagoons. These lagoons may be emptied within their active life by physical removal of the impounded liquid or by evaporation. The pond may be refilled when additional suitable waste material is received or with necessary changes, resulting in a cyclic process of drying out and rewetting the liner material. When a waste lagoon is deemed no longer useful, the liquid may be allowed to evaporate and the facility is then left open to dry. When a lagoon bottom is allowed to dry, the uppermost layer, containing the most adsorbed contaminants, may be eroded by local winds. This action may result in offsite contamination.

An example of such a facility, used for pesticide and other waste disposal is located in southern California. The climate in this area is hot and dry: average annual rainfall is approximately 5 inches while annual evaporation is high (approximately 100 inches). This high rate frequently causes the lagoons to dry out.

Specific information on contamination was not available, but estimates were for a value of 5,571 ppm for the pesticide dieldrin. The soil that lines the 1-acre lagoon contains approximately 40 percent sand, 40 percent silt, and 20 percent clay. Due to the lack of local vegetation, the organic carbon content of the soil is only about 0.1 percent. For example purposes, the facility is assumed to be dry and inactive.

Abandoned drum storage facilities often are not maintained and hazardous materials may seep from corroded drums, contaminating surrounding soil. The soils may be eroded by the wind, thus spreading the contamination to other areas.

Some 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) contamination data are available for a herbicide storage and loading facility in Okaloosa County, Florida (Harrison and Miller, 1979). Between 1962 and 1970, several hundred 55-gallon drums of herbicides were stored around a concrete aircraft pad (approximately 125 feet in diameter) and were loaded onto aircraft. Soil contamination occurred due to spills, leaking drums, purging of aircraft spray systems, and malfunctions of aircraft spray nozzles.

A study by the Air Force Armament Laboratory from January 1976 to December 1978 revealed up to 275 ppb TCDD contamination in a limited area (Harrison and Miller, 1979). Average contamination over one area of approximately 350 m^2 was 32 ppb. Further work by Harrison and Crews (1983) showed levels of 120 ppb.

Soil surrounding the concrete loading pad where the drums were stored was a well-draining sandy soil estimated to contain 90 percent sand, 7 percent silt, and 3 percent clay. The soil's organic carbon content was approximately 1 percent.

Prior to the closure of a landfill, the facility offers great potential for fugitive particulate emissions. Waste placement at a landfill usually requires heavy equipment to spread the waste and, when necessary, to cover it daily with soil. Contaminated soil clinging to equipment or the upper surface of the daily cover is a potential source of fugitive particulate emissions.

A soil-capped landfill has the potential for contaminated cover soil that may be eroded by the wind. Leaking waste materials may evaporate, rise to the cover surface, and then condense, contaminating the cover soil.

A 40-acre soil-capped facility containing toluene and other volatile organics was located in Michigan. Estimated degree of toluene contamination was 3,640 ppm, estimated particle size distribution of cover soil was 25 percent sand, 35 percent silt, 30 percent clay, and 3 percent organic carbon.

SECTION 6
CONTROL TECHNIQUES

This section discusses techniques available to control fugitive particulate emissions from treatment, storage, and disposal facilities (TSDF's). Both active systems (those requiring man's routine intervention) and passive systems (those that are self-sustaining) are described. Emphasis is on identifying techniques demonstrated for sources of fugitive particulate emissions, with some assessment of control efficiency. Although few of these techniques have been evaluated by field sampling at TSDF's, they have been applied and evaluated at sources similar to TSDF's so technology transfer is straightforward. Controls for fugitive particulate emissions have been used on storage piles (especially coal), waste piles (especially mine tailings), paved and unpaved roads, croplands, construction areas, and handling and transfer of bulk solids.

6.1 CHEMICAL STABILIZATION

Chemical dust control methods involve application of one of many available chemicals to the dust source to form a new cohesive surface (e.g., a protective film over the surface), to bind particles together into a coarse agglomerate, or to form a crust. Spray systems that maintain a moist surface and systems that use a foam or surfactant to extend water through improved surface wetting are discussed in Section 6.2, Wet Suppression. Chemical stabilization includes products that function as dust suppressants even after the material has dried, usually 24 to 48 hours after application.

Examples of chemical stabilizers that bind particles together and/or form a new surface include elastomeric or latex polymers, lignosulfonates (calcium, sodium, and ammonium), asphalt emulsions, petroleum by-products, and hygroscopic salts. Rosbury (1984) presented a comprehensive list of chemical suppressants and manufacturers that is partially reproduced in Table 5 to illustrate the wide variety of commercially available products. The classification system in Table 5 was developed by Rosbury and includes bitumens, adhesives, and salts; the adhesives category was the largest, with 44 products identified as potentially applicable to fugitive dust control.

Most chemical stabilizers are liquids diluted with water and applied as a spray. A few are liquids that are applied undiluted, such as waste oil, Peneprime®, and Dust Bond 100®. The hygroscopic salts can be obtained and applied either as a solid or as a water solution. Spraying is the most common method of applying chemical stabilizers. A few experimenters have evaluated admixing the stabilizer with the top few inches of surface particles for comparison with the surface spraying technique.

TABLE 5. CHEMICAL STABILIZERS (Rosbury, 1984)

A. Type: Bitumens

Product	Manufacturer
AMS 2200, 2300®	Arco Mine Sciences
Coherex®	Witco Chemical
Docal 1002®	Douglas Oil Company
Peneprime®	Utah Emulsions
Petro Tac P®	Syntech Products Corporation
Resinex®	Neyra Industries, Inc.
Retain®	Dubois Chemical Company

B. Type: Salts

Product	Manufacturer
Calcium chloride	Allied Chemical Corporation
Dowflake, Liquid Dow®	Dow Chemical
DP-10®	Wen-Don Corporation
Dust Ban 8806®	Nalco Chemical Company
Dustgard®	G.S.L. Minerals and Chemicals Corporation
Sodium Silicate	The PQ Corporation

C. Type: Adhesives

Product	Manufacturer
Acrylic DLR-MS®	Rohm and Haas Company
Bio Cat 300-1®	Applied Natural Systems, Inc.
CPB-12®	Wen-Don Corporation
Curasol AK®	American Hoechst Corporation
DCL-40A, 1801, 1803®	Calgon Corporation
DC-859, 873®	Betz Laboratories, Inc.
Dust Ban®	Nalco Chemical Company
Flambinder®	Flambeau Paper Company
Lignosite®	Georgia Pacific Corporation
Norlig A, 12®	Reed Lignin, Inc.
Orzan series®	Crown Zellerbach Corporation
Soil Gard®	Walsh Chemical

Chemical stabilizers have been evaluated as controls for wind erosion and fugitive dust emissions from unpaved roads at industrial plants and mines, coal storage piles, waste piles of mill tailings, tailings ponds, and croplands. Li et al. (1983) reviewed demonstrated applications of chemical stabilizers for copper production (haul roads and storage piles), molybdenum mining (tailings piles), iron ore production (taconite storage and tailings), coal production and use (haul roads, transport, and storage), uranium production (tailings), Agricultural Soil Conservation Service (croplands), highway construction, electric utilities (storage of finely ground coal), and the military (roads and airports). Focusing on controls for wind erosion of uranium mill tailings, Li et al. concluded that chemical stabilizers had been demonstrated and could be an effective control technique.

Lyles and Armbrust (1969) investigated the use of four spray-on adhesives for wind erosion control of croplands. Field plots of soil containing 89.6 percent sand, 5.9 percent silt, and 4.5 percent clay were prepared by disking and raking to make it highly erodible. Test plots were sprayed with chemical adhesives and then tested after 16 to 24 hours. The soil moved by a 1.6-m/s (35-mph) wind from a portable wind tunnel was measured 0.3 m (1 ft) above the surface. An untreated plot was used as the control.

Results are shown in Table 6 and indicate that as the application rate increases for all four products, soil movement decreases. A further reduction in soil movement was noted for all products by increasing the dilution rate and maintaining the highest application rate; however, this improvement was short term because the highly dilute applications failed after 4 weeks. Visual inspection revealed numerous holes in the surface film, which was apparently too thin. All stabilizers used at the manufacturer's recommended dilution and application rate were holding well against natural winds 7 weeks after testing. This study also found a fine spray (agricultural nozzle) to be superior to a coarse spray (industrial nozzle) when stabilizers are applied.

Armbrust and Dickerson (1971) investigated 34 commercially available materials for soil stabilization and wind erosion control. An erodible soil with the same composition as previously described was tested with application rates of 4, 2, 1, 1/2, 1/4, and 1/8 times the recommended rate. Trays of treated soil were exposed to a 1.3-m/s (30-mph) wind for 10 min in a wind tunnel. Other trays were placed outside (in sun and rain) for 60, 120, and 180 days before testing in the wind tunnel to weather them. Materials were evaluated by the following criteria: (1) prevent erosion completely upon initial application and reduce it for at least 2 months, (2) have no effect on plant germination or growth, (3) are easily applied, and (4) cost less than $0.012/m² ($50/acre). Six products met all of the criteria and are listed in Table 7. The weathering tests for four of these six products ranged from 79 (for Coherex®) to 33 percent (for Polyco 2460®) reduction in soil movement after 60 days of weathering. All of the 34 materials originally tested provided temporary wind erosion control, and all but 8 chemicals reduced soil loss for 60 days. Therefore, chemicals must be selected based on additional criteria, such as cost, application ease, and potential for other beneficial or adverse impacts.

TABLE 6. CHEMICAL STABILIZERS FOR AGRICULTURAL SOILS
(Lyes and Armbrust, 1969)

Stabilizer	Dilution with water	Application (L/m²)	Application (gal/acre)	Percent reduction in soil movement
Swifts Resin Adhesive Z-3876®	2:1	0.81	870[a]	94
	2:1	0.41	435	68
	2:1	0.20	218	36
	12:1	0.81	870	99
Coherex®	4:1	1.13	1,210[a]	99
	4:1	0.57	605	96
	4:1	0.28	303	84
	19:1	1.13	1,210	99.5
Anionic asphalt emulsion	1:1	1.13	1,210[a]	99
	1:1	0.57	605	93
	1:1	0.28	303	85
	7:1	1.13	1,210	99.8
Oil/latex polymer	3:1	1.12	1,200[a]	99.3
	3:1	0.75	800	98
	3:1	0.37	400	87
	11:1	1.12	1,200	99.6

[a] Manufacturer's recommended rate.

TABLE 7. STABILIZATION CHEMICALS SELECTED
(Armbrust and Dickerson, 1971)

Product	Manufacturer	Application rate[a] (L/m^2)	Application rate[a] (gal/acre)	Percent soil loss[b]
Coherex®	Witco Chemical Co.	0.16	170	21
DC-70®	Union Carbide	0.016	17	c
Petroset SB®	Phillips Petroleum Co.	0.021	22	c
Polyco 2460®	Borden Chemical Co.	0.016	17	67
Polyco 2605®	Borden Chemical Co.	0.016	17	37
SBR latex S-2105®	Shell Chemical Co.	0.016	17	57

[a] Costs were $26.90 to $49.50 per acre (1971 dollars).

[b] After 60 days of natural weathering and expressed as percent of control sample loss.

[c] These products were received too late for weathering tests but met all other criteria. Armbrust and Dickerson concluded control of these products would be similar to control of the other products because of their similarities.

Sultan (1976) tested 46 commercially available chemicals for control of dust and erosion on dune sand (for wind erosion) and compacted granitic soil (for traffic erosion). The chemical treatments were subjected to freeze-thaw cycles, wet-dry cycles, and various curing temperatures. Soil movement was measured after test specimens were subjected to 2.0-m/s (45-mph) and 4.0-m/s (90-mph) winds. Of 27 chemicals, 14 successfully endured the various environmental conditions and continued to reduce wind erosion by at least 95 percent compared to the untreated control sample. The rain-dry cycle imposed the highest erosion rates. The lignin-based products, because of their high-water solubility, experienced the highest erosion rates after the rain-dry cycle.

The granitic soil samples were treated and tested for traffic erosion control under the wind conditions described above plus another condition of simulated tire abrasion. Of the 19 chemicals tested, 8 resulted in erosion losses less than 1/2 percent of control samples losses. Study results indicate that chemical stabilizers can significantly reduce wind erosion of dune sands and traffic erosion of unpaved roads.

In a continuation of the initial study, stabilizers were applied to sections of an unpaved road with an average daily traffic of 140 vehicles and a silt content of 28 percent (EPA, 1982a). Some of the chemicals were applied topically by spraying, and others were mixed to a depth of 7.6 cm (3 in.) and compacted. After 5 months, control efficiencies of 83 to 95 percent were still being achieved. Results showed that working the stabilizer into the road surface made it effective for a longer time period (EPA, 1982a).

Rosbury and Zimmer (1983) reported on four types of chemicals and water to suppress dust from coal mine haul roads containing 50 to 74 percent fines. The four types of chemicals included a salt (calcium chloride), a surfactant (Soil-Sement®), an adhesive (lignosulfonate), and a bitumen (Arco 2200®). Field sampling for particulate matter was conducted with a vertical exposure profiler that takes samples at four different heights. Testing was hindered and emission levels were depressed because of 12 storms (19 cm of rain) over the 38-day period. Control efficiencies of 40 to 60 percent for suspended particulate matter were observed for all of the products over the first 2 weeks following application and then decreased with time. Watering once per hour resulted in 45 percent control, and watering twice per hour yielded about 55 percent control.

The cost effectiveness at 50 percent control was evaluated for calcium chloride, lignosulfonate, and watering. The surfactant and bitumen products were not included in the cost analysis because the necessary reapplication rates could not be estimated. The most cost-effective controls were topical applications of calcium chloride ($1,000/wk to $1,400/wk), lignosulfonate mixed with the road surface ($1,300/wk to $2,100/wk). Water was the least cost-effective option at about $2,100/wk. These costs were based on a road width of 15 m (50 ft) in the East and 18 m (60 ft) in the West.

The authors emphasize that control efficiency should be evaluated no earlier than 48 hours after application because the surface is still moist 24 to 48 hours later. Testing before the 48-hour period may actually evaluate the effect of increasing surface moisture on dust control. Rosbury (1984) summarized control efficiencies from the literature and showed a range of 83 to 99 percent control for tests conducted 1 to 2 days after application. For tests conducted 3 days to 3.5 months after application, control efficiency ranged from 0 to 95 percent, with most test results ranging from 35 to 89 percent. These data clearly indicate the variable long-term control effectiveness for unpaved roads.

Russell and Caruso (1983) investigated the use of Coherex®, lignosulfonate mixed with Arcoat 220®, and oil well brine to control emissions from unpaved roads in the iron and steel industry. (Oil well brine is a waste product from crude oil production that functions as a hygroscopic salt.) The percent silt in the surface material and high-volume air sampling were used to evaluate control effectiveness. A small truck traveling at 0.7 m/s (15 mph), in addition to normal road traffic, was used to generate dust. The road test section was exposed to significant abrasion from a high daily traffic count (307 to 316 vehicles), which resulted in silt formation.

Results are given in Table 8 and show control efficiencies greater than 90 percent for all three products for the first 4 weeks. The percent control of silt is also shown and, except for oil well brine, appears to be well correlated to TSP. Silt and TSP for oil well brine do not correspond as closely because the treated surface, when sieved, broke into small particles that reagglomerated after passing through the screen.

Oil well brine was applied on five different occasions before the test until the road's silt content was 0 percent. Because of dust redeposition from an adjacent untreated section, the oil well brine was reapplied after 4 weeks. Although more oil well brine was applied, its cost effectiveness was superior to that of the other products, primarily because the material was free (including the labor to apply it to the road). Under these conditions, few products can be more economical than oil well brine.

Cowherd (1979) reported on the use of a 10-percent solution of Coherex® in water on a dirt/slag road in an iron and steel plant. The road is used by light- and medium-duty vehicles. An initially high control efficiency (>90 percent) for suspended particulate matter decreased by more than 10 percent with passage of 200 to 300 vehicles. The stabilizer's performance was adversely affected by tracking of dust from untreated sections of the road. Cowherd (1979) also reported on the use of ammonium lignin sulfonate on a haul road composed of waste rock aggregate at a taconite mine. A 20- to 25-percent solution of retardant was sprayed at a rate of 0.36 L/m^2 (0.08 gal/yd^2). The initially high efficiency (>90 percent) gradually deteriorated to roughly 80 percent after the passage of 300 vehicles. Personnel at the taconite mine stated that the binding properties of the lignosulfonate could be partially restored by wetting. Cowherd et al. (1982) discuss additional tests that were conducted at a steel plant to control emissions from unpaved roads. They reported a control efficiency of 92 percent for total particulate from light-duty traffic and 96 percent

TABLE 8. PERCENT REDUCTION IN SILT AND TSP
(Russell and Caruso, 1983)

Time since application (weeks)	Lignosulfonate + Arcoat 220®		Coherex®		Oil well brine	
	Silt (%)	TSP[c] (%)	Silt (%)	TSP (%)	Silt (%)	TSP (%)
2	96	96[a]	100	99[a]	100	99[a]
3	88	95	97	94	79	91
4	74	90	96	93	71	92
5	74	74	98	88	93[b]	95[b]
6	47	34	68	71	34	83

[a] Not measured; extrapolated value from percent silt.

[b] Oil well brine was reapplied.

[c] TSP - Total Suspended Particulate

from heavy-duty traffic after application of Coherex®. Watering on an 8-hour cycle reduced emissions from heavy-duty traffic 50 percent. The corresponding control efficiencies in terms of inhalable particles were 91 percent for light-duty traffic and 95 percent for heavy-duty traffic. Watering reduced inhalable particles for heavy-duty traffic 63 percent. Cowherd concluded that the chemical stabilizer's control efficiency was independent of particle size. He also emphasized that the efficiency of Coherex® represents only the early stage in its expected lifetime.

Runnels (1983) reported on fugitive dust control on unpaved haul roads at a dry-process cement plant. The plant first tried water sprinkling for dust control but eventually rejected watering because of the long application time for loading, transport, and spraying and the short life of the dampness. Calcium chloride was also tried and worked well initially, but it too was short lived. A light rain completely eliminated the calcium chloride; but even where it did not rain, heavy traffic cut through the surface layer, often on the same day of application. Runnels also reported that calcium chloride was corrosive to the plant's vehicles. Oil that was available locally was also tried; however, too much time and labor were needed to obtain the oil, prepare the surface, and add road rock.

The cement company concluded that Coherex® offered the best combination of effectiveness and cost for its plant. Coherex® has been used since 1974 at an average rate of 59,800 L/yr (15,800 gal/yr) to control dust at the plant. The company's experience indicates that it is essential to allow adequate time (overnight at a minimum) for the Coherex® solution to penetrate before allowing traffic on the road. A uniform and even application of the diluted material (9:1) is also important. Benefits cited included good dust control, reduced maintenance requirements for the company's large trucks, and cleaner vehicles leaving the plant.

Canessa (1977) reported that Utah International used Coherex® for dust control from unpaved roads at its coal mine. For new roads, the dust retardant is added at 10 percent dilution with water, worked into the surface, and compacted. This procedure is repeated for the new roads for several days until the surface is dust free. For old roads, the dust retardant was diluted to 0.4 percent with water and applied. At this dilution rate, the Coherex® acts only as a water extender.

Morwald (1983) reported on dust control of unpaved roads at Dofasco's integrated steel plant in Hamilton, Ontario. The plant has 17.4 km of unpaved roads that are sprayed with oil for dust control. He estimates that an 85-percent control efficiency has been obtained for unpaved roads. Oil application is required every 3 days for unpaved roads, compared to the plant's estimate of a once-per-day requirement for Coherex® and lignin products.

Roberts et al. (1975) stated that for the case he studied (Seattle), oiling was the most economical method to control fugitive dust from gravel roads with an average daily traffic greater than 15 vehicles. For daily traffic exceeding 100 vehicles, paving was recommended to reduce health risks and property damage. Cooper et al. (1979) stated that their correspondence with State highway departments showed that oiling was not particularly attractive for short-term control. They estimated 50 to 90 percent dust control from oiling with an annual maintenance cost of $680/km ($1,100/mi). Annual maintenance of a gravel road was estimated as $1,800/km ($2,900/mi). Cooper et al. (1979) found that North Dakota and Virginia used calcium chloride on dusty roads. At relative humidities over 29 percent, calcium chloride absorbs moisture from the air to suppress dust. The cost of calcium chloride treatment was estimated as $250/km-wk ($400/mi-wk) by North Dakota and $0.06/m^2 ($0.05/yd^2) by Virginia.

Dean et al. (1974) investigated the use of chemicals for stabilizing fine-sized mineral wastes that are discarded by ore milling plants. Seventy chemicals were tested on acidic, basic, and neutral mill tailings for resistance to water and air erosion. The chemicals were evaluated based on a combination of effectiveness and cost with the following general conclusions.

- Coherex® provided good wind resistance at an application rate of 0.22 L/m^2 (240 gal/acre) and provided water resistance at 2.2 L/m^2 (2,400 gal/acre).
- Lignosulfonates were effective at 0.27 kg/m^2 (2,400 lb/acre).
- Compound SP-400®, Soil Gard®, and DCA-70® were effective at 0.051, 0.084, and 0.047 L/m^2 (55, 90, and 50 gal/acre), respectively; all were exceptionally effective on sandy tailings.

Other compounds that were effective, by increasing cost, were cement and milk of lime, Paracol TC1842® (a resin emulsion), Parmak WTP® (wax, tar, and pitch), Petroset SB-1® (an elastomeric polymer), potassium silicate, and PB-4601® (a polymer).

Havens and Dean (1969) tested two chemicals, DCA-70® (an elastomeric polymer from Union Carbide) and calcium lignosulfonate, on uranium mill tailings at Tuba City, Arizona. DCA-70® was applied at an average rate of 0.24 L/m^2 (0.053 gal/yd^2), and the calcium lignosulfonate was applied at a rate of 0.5 kg/m^2 (0.93 lb/yd^2). The tailings were inspected after 1, 2, and 4 years. Surface disruption was found to be about 10, 20, and 40 percent, respectively, during these inspections but was caused primarily by human activity (i.e., walking and digging). With proper application and maintenance, the study concluded that the stabilizers could be effective for a long time.

Dean et al. (1969) also investigated the stabilization of tailings from a Nevada copper mill. The tailings consisted primarily of quartz and feldspar with a high percentage of fines (59 percent passing through a 200-mesh screen). The program's goal was to evaluate the use of a combination of vegetation and chemical stabilization. Because of its compatibility with vegetation and its cost advantage, Coherex® was chosen for evaluation on a 40,500-m^2 (10-acre) section of the tailings. The Coherex® satisfactorily maintained the surface until the vegetation grew, and the stabilized tailings with vegetation appeared to be fully resistant to wind erosion after 1 year of observation. The application rate ranged from 0.16 to 0.59 L/m^2 (0.036 to 0.13 gal/yd^2); however, no differences in erosion control were noted for the various application rates. After 6 years of observation (Dean et al., 1974), during which many violent windstorms passed through the area without raising dust clouds from the stabilized plots, vegetation has continued to improve with about 27 different plant species growing well. Following this test chemical/vegetative stabilization was used successfully on 100 more acres at the Nevada site; on tailings in different climates, and on different mineral bases in Colorado, Michigan, Missouri, and Washington.

Bohn and Johnson (1983) investigated chemical stabilization of tailings from a taconite processing plant in Minnesota. Four types of stabilizers were tested (Coherex®, calcium lignosulfonate, two latex polymers, and magnesium chloride) on 2,000-m^2 (0.5-acre) plots of the tailings pond. A wind tunnel and suspended particulate sampling were used to evaluate the tailings' wind erosion potential. The study found that rainfall was the meteorological factor that most affects control efficiency and, when coupled with high winds, produces a synergistic effect that lowers the threshold velocity.

The study evaluated the costs for attaining 75 and 90+ percent control for all four types of products. At best, reapplication of the stabilizer is required every 6 to 8 weeks. The most effective stabilizers (lignosulfonate at 4:1 dilution, latexes, and magnesium chloride) were estimated to require only one additional application (total of two applications) over a 3-month period. The other stabilizers (petroleum resin and lignosulfonate at 8:1 dilution) required multiple applications. The most cost-effective stabilizer to achieve 75 and 90+ percent control was the calcium lignosulfonate at \$0.032 to \$0.048/m^2 (\$130 to \$195/acre), and the least cost-effective was magnesium chloride at \$0.78/m^2 (\$3,165/acre). The authors point out that because of shipping costs, the user's site location and the chemical's origin can significantly affect the cost-effectiveness evaluation. As an example, the cost of the lignosulfonate increases to \$0.069 to \$0.11/m^2 (\$280 to \$450/acre) for Utah/Wyoming, and the cost of magnesium chloride decreases to \$0.26/m^2 (\$1,050/acre) for chemicals shipped from the same locations used for the Minnesota site.

McKell and Van Epps (1980) evaluated chemical stabilizers in the vegetative rehabilitation of arid land disturbed during development of oil shale and coal. Soil stabilization reduced soil surface looseness and promoted runoff to help establish vegetation. The stabilizers' effectiveness lasted for only a year. McKell and Van Epps noted that slopes stabilized and competition from weedy annual plants decreased. They found that an insufficient coating of stabilizer had no beneficial effect but that a good coating doubled water runoff.

Canessa (1977) reported that Consolidation Coal treated 59,000 m^2 (14.5 acres) of dry slurry lagoons with Coherex®. The lagoons contained fine reject material composed of coal, ash, and pyrite. A 1:6 dilution was applied to the dried-out lagoon at a rate of 4.5 L/m^2 (1 gal/yd^2). The dust from the lagoon was suppressed, vegetation grew, and control efficiency was deemed better than that of a grass cover alone.

Drehmel and Daniel (1982) evaluated chemical treatments to suppress fugitive emissions from coal dust. Effectiveness was evaluated in a wind tunnel based on entrainment velocity, which was defined as wind velocity required to entrain 10 g/min. For a fixed cost of $750/ha ($300/acre), entrainment velocity after treatment with each chemical was estimated:

	Entrainment velocity	
Chemical	(m/s)	(mph)
SP-301®	0.94	21
Pentron DC-3®	1.3	30
CPB-12®	1.4	32
Coherex®	2.0	44
Polyco 2151®	2.2	50
Coal Dyne®	2.5	55
Oil and water	2.7	60
Lignosulfonate	2.7	61

The SP-301®, Pentron DC-3®, and CPB-12® were the least cost effective, whereas the oil and water and lignosulfonate were the most cost effective. The effect of application rate on entrainment velocity varied. The study found that an increased application rate proportionately increased effectiveness for the lignosulfonate, Coherex®, CPB-12®, Polyco 2151®, and Coal Dyne®. An increased rate for SP-301® caused a rapid rise in effectiveness. However, an increased application rate had little or no effect on the effectiveness of Pentron®. All of the additives tested reduced entrainment velocity, and all except Coal Dyne® were effective at the manufacturer's recommended dilution rate.

Morwald (1983) reported that stabilizers were used to control fugitive emissions from coal storage piles at Dofasco's steel plant. The coal piles were first compacted and smoothed with a roller and then sprayed with waste oils. He estimated 95 percent control of the storage pile particulate emissions by this procedure. He also stated that a successful long-term emission control program requires (1) constant monitoring of equipment, dust, and weather conditions; (2) competent personnel; and (3) a commitment by management to the control program.

6.2 WET SUPPRESSION

Wet suppression techniques can be used to control fugitive particulate emissions by spraying a liquid on the surface of the emission source. Historically, water sprays have been used for this purpose to cause small dust particles to adhere to larger pieces and thus prevent entrainment. From the wind erosion equation, the wind erosion rate varies inversely as the square of the soil moisture (Donovan et al., 1976). Water sprays have been used to control emissions from plant and mine haul roads, storage piles, bulk solid transfer points, cattle feedlots, and construction areas. Spraying from trucks or from fixed pipelines are two common application methods (EPA, 1982a).

Water is short lived and therefore requires frequent repeated applications to maintain effectiveness. In arid areas, where inherent dryness and wind promote wind erosion, water may be a relatively scarce resource and an impractical control option. Depending on the nature of the source and its location, water loss from evaporation or runoff may be significant. Before water is selected for dust control, potential for increased leachate generation and spread of the contaminant to adjacent soil, surface water, or groundwater must be evaluated.

Water has a relatively high surface tension, which inhibits its ability to spread and thoroughly wet many materials. A surfactant or wetting agent often is added to the water to decrease the surface tension to allow the water to spread further, penetrate deeper, and to wet the small particles better than water alone. Foam is also used in wet suppression and is effective because small particles break the surface of the foam, become wetted, and agglomerate after contact with other small particles or with larger particles (EPA, 1982a). For example, Seibel (1976) found that foam was more effective than water sprays in controlling respirable dust at a coal transfer point.

Spray systems can reduce emissions from load-in of storage piles by 70 to 90 percent and from wind erosion by 80 to 90 percent. Other reported control efficiencies for spray systems are 80 percent for cattle feedlots, 70 percent for construction operations, and 30 to 50 percent for unpaved access roads (watering twice per day at 2.3 L/m^2) (EPA, 1982a).

Zimmer (1983) evaluated water spraying as a control for unpaved coal mine haul roads. He reported that watering once per hour reduced TSP's 45 percent and that watering twice per hour reduced TSP's 55 percent. Cowherd et al. (1982) discussed watering as a control measure for unpaved roads used by heavy-duty vehicles at a steel plant. For an 8-hour watering cycle, a 50-percent reduction was reported for TSP's, and a 63-percent reduction was reported for inhalable particles.

Runnels (1983) reported on his cement plant's unsuccessful attempt to use water to control emissions from unpaved roads. Water sprays were abandoned because of the lengthy loading and spraying time and the short life of the surface moisture. Morwald (1983) reported that fixed water sprays were once used to control emissions from Dofasco's coal storage piles; however, waste oil was found to be more effective and is currently used instead of water.

Construction contractors usually use watering trucks to reduce dust generation at a construction site. Their need to control dust is dictated by worker demands and high equipment maintenance costs. Water provides adequate dust control if it is repeated frequently at a sufficient application rate. It can be a low-cost option because most construction jobs already have the necessary equipment and facilities for the task (Jutze and Axetell, 1974).

Chemical wetting agents or foam also can be used to control emissions from open storage piles. Control efficiencies of 80 to 90 percent are reported for emissions from loading onto piles, 90 percent for emissions from movement of the pile, and 90 percent for wind erosion (EPA, 1982b).

6.3 PHYSICAL COVERING

Stabilization by covering the surface is an effective control technique for inactive fugitive emission sources, such as abandoned waste stockpiles or dried-up lagoons. The emission source can be covered with a layer of rocks, soil, bark, slag, wood chips, or straw to enclose the exposed surface, which eliminates wind penetration and contact with fine particles that may otherwise become airborne (EPA, 1982a).

Vogel and O'Sullivan (1983) discussed using domes or partially enclosed structures, such as those used for storing gravel or sand by highway departments, that could provide almost 100 percent emission control. Synthetic covers are another device used to eliminate emissions. The cost of a dome with a 15-m (50-ft) diameter and 604-Mg (664-ton) capacity was estimated as $46,000. The cost increases to about $80,000 for a 30-m (100-ft) diameter and 4,200-Mg (4,650-ton) capacity dome and includes materials, installation, wiring, lighting, and ventilation. The cost of synthetic covers was estimated as $13/m^2 to $20/m^2 ($4/ft^2 to $6/ft^2) on a completely installed basis. The cost for covering a median size waste pile of 280 m^2 (0.07 acre) was estimated as $7,000 to $14,000 (Vogel and O'Sullivan, 1983).

One type of synthetic cover that is applied as a foam has been used in Europe for several years in sanitary landfills as a substitute for a 6-inch soil cover. The foam is a urea-methylene complex that dries, hardens, and forms an effective dust cover (Vogel and O'Sullivan, 1983). The foam may be practical for covering wastes after they are placed and compacted in an active landfill; however, the foam cover's integrity is destroyed if heavy equipment is operated on the cover or if wastes are added on top of the foam cover. Material and application labor costs are about $2.15/m^2 for a 5-cm layer, and the application equipment costs approximately $4,000 (Vogel and O'Sullivan, 1983).

Enclosure of open storage piles can reduce fugitive emissions from loading onto the piles by 70 to 99 percent, from movement of the pile by 95 to 99 percent, and from wind erosion by 95 to 99 percent (EPA, 1982b).

Unpaved roads are also emission sources that have been controlled by physical covering. For example, adding gravel to an unimproved dirt road may reduce emissions by 50 percent (EPA, 1982a). Paving covers the emission source and can provide a control efficiency of 85 percent (EPA, 1982a). (Paved roads do not provide 100 percent control because of tracked-in or blown dust and dirt as well as unpaved road shoulders.)

Road carpets are another form of physical cover for controlling emissions from roads. A water-permeable polyester fabric that is laid between the roadbed and the coarse aggregate road ballast (e.g., gravel) separates fine soil particles in the roadbed from the aggregate. The fabric prevents fine materials from moving from the subsoil to the road surface, where entrainment could occur. Any fine materials in the road surface are washed through the fabric and into the subsoil or edge of the road (EPA, 1982a). These civil engineering fabrics have been used for road stabilization, support, drainage, erosion control, and reinforcement. Fabrics are available in strengths sufficient to take loads from haul trucks, are rot resistant, have an estimated useful lifetime of 12 years, and cost about \$1.20/m^2 (\$1.00 yd^2) in 1980 (Levene and Drehmel, 1981).

A road carpet was tested on a 305-m (1,000-ft) segment of unpaved road on a military installation in Colorado. The road is used by light-duty vehicles and occasionally by larger or heavy-duty vehicles. Control effectiveness was measured in terms of reduced concentration of ambient particulate matter. The road covered with fabric and aggregate material resulted in an average 47-percent reduction (range of 30 to 70 percent) in TSP's compared to the uncontrolled test section. Inhalable particles averaged 43 percent reduction with a range of 26 to 53 percent. For both total and inhalable particles, greater reductions were seen at lower windspeeds (Levene and Drehmel, 1981).

6.4 VEGETATIVE COVERING

Abandoned or inactive sites (e.g., landfill covers, impoundment covers, waste piles, road shoulders, reclaimed land, or disturbed soil) are candidates for vegetative stabilization to reduce fugitive emissions. Vegetation is an impractical control option for active sites because of disruption of the cover and damage to the vegetation. The primary control mechanism is direct stabilization of the soil surface: the roots bind the soil, and the plant stems and leaves form a protective cover, preventing particles from becoming airborne. Two minor control mechanisms from vegetation are (1) the windbreak effect of plants planted perpendicular to the direction of prevailing wind, and (2) the removal of dust particles from the air by plants (vegetation is a natural filter that removes dust by impaction) (Donovan et al., 1976). Another use of vegetation is to form shelter belts, usually growths of trees or shrubs, that shelter the dust source primarily from the wind but also from the sun.

Vegetative stabilization is sometimes used in combination with physical or chemical stabilization techniques. The combined approach prevents sandblasting of vegetation, aids in moisture retention, and allows the vegetation to germinate and grow (Dean et al., 1974). Several examples of combining vegetative/chemical stabilization for abandoned tailings piles are discussed in Section 6.1, Chemical Stabilization.

The control efficiency of a vegetative cover varies with the type and amount of cover. In the arid Southwest, particulate emission reductions may be as low as 25 percent; in areas that can support a dense vegetative cover, control efficiency may approach 100 percent (EPA, 1982a). In some cases, the combined effects of climate and composition of the waste pile may resist growth because of salt, heavy metals, windblown sand, high temperature, and lack of water (Li et al., 1983). Some considerations in selection of vegetative covers include (Li et al., 1983):

- Plants should be able to thrive under existing soil, moisture, and exposure conditions.

- Plants should be rapid growing to provide early protection.

- Plants that produce their own mulch control erosion best.

- Plants should be resistant to insects and disease and should be nonpoisonous.

Soil composition, nutrients, and compatibility with plants also should be evaluated before a particular plant species is selected.

Lutton et al. (1979) recommend the use of vegetation on landfill covers, primarily to control water erosion but also to control wind erosion. Deep-rooted plants should be avoided in this application to prevent root penetration of the impermeable clay or synthetic cap that is placed over the waste to limit water infiltration.

6.5 WINDSCREENS

Windscreens are barriers placed perpendicular to the direction of prevailing wind to reduce windspeed and penetration of the source's surface. Soo (1980) reported that wind barriers can reduce wind penetration into storage piles by 50 percent to reduce dust emissions and to decrease moisture loss from the pile. A barrier with a height that is 25 to 50 percent of the height of the pile, placed about 2 to 3 pile heights away, reduces wind penetration and dust lift by 25 to 60 percent (Soo et al., 1980).

Lawrence (1983) described the preliminary results of a study by Larson (TRC Environmental Consultants) on the effectiveness of windscreens at reducing emissions from a fly ash pile. He concluded that wind velocity could be reduced by about 66 percent with corresponding reductions of 75 percent for TSP's and 60 percent for inhalable particles.

Drehmel and Daniel (1982) conducted preliminary tests of windscreens in a flat field near an airport. The two windscreens that were tested had permeabilities of 65 and 50 percent and were 1.8 m high. For the 65-percent permeable screen and an average incident windspeed of 3.0 m/s, an average wind velocity reduction of 70 percent was reported in the downwind area. This reduction decreased to 40 percent for an average incident windspeed of 5.2 m/s. For an incident windspeed of 4.2 m/s, the 50-percent permeable screen reduced the wind velocity by 60 percent.

Application of a windscreen for a coal storage pile was evaluated theoretically. Drehmel and Daniel (1982) concluded that windscreens are effective for dust control and can reduce emissions from a coal storage pile by up to 80 percent.

Wind breaks can reduce erosion on a typical 600-m-long field by 12 percent; however, they are generally not feasible for large fields. The effectiveness extends downwind for a distance equal to approximately 10 times the barrier height (EPA, 1982a).

Vogel and O'Sullivan (1983) reported that a polyester windscreen 1.8-m (6-ft) high costs about \$43 per linear meter (\$13 per linear foot) installed. Screens of other heights cost \$22/m^2 to \$27/m^2 (\$2/ft^2 to \$2.5/ft^2), including the screen, mounting hardware, post erection, and installation. The cost for installing a 3-m (10-ft) high fence around a median size waste pile of 280 m^2 (0.07 acre) was estimated as \$4,000.

6.6 SPEED REDUCTION

For unpaved roads, particulate emissions increase as the speed of the vehicle increases if all other factors remain constant. Speed reduction reduces the turbulence and energy imparted to fine particles, which reduces entrainment. One report states that emissions are proportional to the square of vehicle speed (EPA, 1982a). The following reductions in emissions are estimated from an arbitrarily chosen starting point (or uncontrolled case) of 64 km/h:

Speed		Percent reduction in emissions
(km/h)	(mph)	
64	40	0
48	30	25
32	20	65
24	15	80

Cooper et al. (1979) presented results for a similar model that incorporated a term for the average daily traffic. Results are listed below and are generally consistent with emission reductions provided earlier.

Speed		Percent reduction for average daily traffic of		
km/h	mph	50	500	Infinite
64	40	0	0	0
48	30	38	47	48
32	20	58	71	73

6.7 PREVENTION AND CONTROL OF CONTAMINATION

The previous sections focus on techniques that control fugitive emissions of contaminated soil particles. These techniques are remedial actions to control the airborne spread of pollutants after soil contamination has occurred. An obvious way to control fugitive emissions of contaminated soil is to prevent initial soil contamination from occurring. Preventive measures may eliminate or forestall the need for remedial techniques to control contaminated particle emissions.

Current regulations for TSDF's are presented in Title 40, Parts 264 and 265 of the Code of Federal Regulations (CFR) (July 1, 1983) and specify several requirements that minimize the probability of soil contamination. Provisions for containers and tanks in Subparts I and J require that both be in good structural condition and leak free. Containers must be compatible with the waste, kept closed, handled in a manner to prevent rupture, and inspected once per week. Tanks are to be protected from corrosion and overfilling and must be inspected daily. At closure, all hazardous materials must be removed or decontaminated. The requirements for new container facilities with free liquids are more stringent and further minimize the probability of contaminating soil through the containment requirements of §264.175. A base that is sufficiently impervious to leaks and spills is required under the storage area. Spills, leaks, run-on, and run-off from precipitation are collected and removed. Therefore, potential for soil contamination and for airborne distribution of the soil particles is much greater for an existing facility that does not have a liquid collection and removal system. A new facility that has incurred the cost of an impervious base and a liquid collection system that is properly operated and maintained can have a control efficiency approaching 100 percent for contaminated fugitive particulate emissions.

Several design and operating requirements are also provided for new tanks and are not specified for old tanks. These design and operating requirements, such as minimum shell thickness, inner liner, and corrosion protection further reduce the probability of tank failure and soil contamination. Surprisingly, dikes are not required around old or new tanks containing hazardous waste.

For both new and existing surface impoundments, routine inspection of the dike area and vegetation is required once per week and after storms. Overtopping by wave action, overfilling, or a storm can contaminate soil and is prevented by maintaining sufficient freeboard. At closure, any hazardous waste must either be removed and disposed of or the impoundment must be closed, covered, and provided with post-closure care as for a landfill.

Emissions from a dried-up impoundment are eliminated, if the solids are hazardous, by requirements to remove the waste and dispose of it properly or to close the facility as a hazardous waste landfill. In addition, new surface impoundments are required to have an impervious liner that contains the liquid contaminant to adjacent soil. An existing facility without the liner has a much higher probability of contaminating soil around the facility.

Both new and existing waste piles containing particulate matter subject to wind erosion must be covered or otherwise managed to control wind dispersal. The waste piles must be inspected once per week and after storms, including the proper functioning of wind controls. New waste piles not completely enclosed to prevent liquid generation, run-on, and wind dispersal must have a liner and a leachate collection system to control leachate migration. Hazardous materials must be removed or secured at closure. Again, requirements for new waste piles afford greater protection from soil contamination by the liquid containment and removal requirements.

For land treatment, the operator must show that the waste can be made less hazardous or nonhazardous by degradation or reactions in or on the soil. Wind dispersal of particulate matter must be controlled and the facility inspected once per week.

Existing landfills must have controls for run-on and run-off of precipitation and must cover or otherwise control any hazardous waste subject to wind dispersal. Bulk or containerized waste with free liquids cannot be placed in a landfill without a liner and leachate collection system unless free-standing liquids are removed. At closure, the site must be covered to prevent migration, water infiltration, and erosion.

New landfills have similar requirements and, in addition, must have a bottom liner and a leachate collection system. This requirement decreases the probability that liquid will spread and contaminate adjacent soil. Weekly inspections are required to detect failures in the liquid movement and wind dispersal controls. Control of liquid movement at new and existing landfills is a preventive measure that can effectively control the contamination of soil particles subject to wind dispersal.

In summary, the recurring difference in preventive measures between new and existing TSDF's is the more stringent control of liquid movement for new facilities. For this reason, remedial control techniques for fugitive particulate emissions are more likely to be needed for older existing facilities, where soil contamination has already occurred or is incipient.

Although operating and control measures are preventive, they do not eliminate the possibility of soil contamination. Equipment failures and human errors occur and can negate the best intentions in design and maintenance. For example, containers, tanks, and liners can fail unexpectedly. Transfer operations can result in leaks or spills from faulty equipment, overfilling of tanks, loading onto a waste pile or landfill, and removal of material from the site or from uncovered or leaking transport. The site, its adjacent land area, and access roads can be contaminated by these equipment or human failures. Because soil contamination cannot be prevented absolutely at new and existing sites, fugitive emission controls may be needed at some point in the lifetime of a TSDF.

Other options in the form of spill control or waste pretreatment are available to minimize the probability of soil contamination and subsequent wind dispersal. When a leak or spill occurs, absorbent material can be used to control liquid movement, and the contaminated soil can be removed and properly disposed of before wind dispersal occurs. Wastes can be containerized, encapsulated, or covered to decrease fugitive emissions during transport or unloading at the site. Pretreatment techniques, such as detoxification, fixation, or vitrification can decrease or eliminate soil contamination if spills do occur.

Extreme measures, such as incineration or disposal in a landfill, can be considered as control options that would prevent fugitive emissions of contaminated soil particles. Current research may offer more economical and efficient alternatives. For example, enzymatic, microbial, and other biological degradation techniques currently are being investigated as mechanisms for decontaminating soil.

SECTION 7
CONTROL EFFECTIVENESS AND COST

The previous section described methods of controlling treatment, storage, and disposal facilities (TSDF's) with emphasis on the various control techniques. Because one technique may be used for more than one type of site, this section describes control effectiveness and cost with emphasis shifted to the type of source being considered.

Control effectiveness has been evaluated in different ways by different experimenters. Some of the data were reported from high-volume air sampling, which yields a control efficiency by reducing total suspended particulate (TSP) matter. In a few cases, reduction in total inhalable particulate matter also is reported. Another method reports reduction in percent silt on the surface after treatment. The silt or fines content of the surface material is determined by the fraction passing through a 200-mesh (74-μm) screen. This size represents the upper limit for particles that can become airborne and thus provides insight into the surface's dust generation potential (Cowherd, 1979). Several studies show a direct relationship between percent silt on the surface and total suspended particles in air. In studies of cropland wind erosion, soil movement is measured to determine control efficiency. Suspension is the mechanism of interest for TSDF's; however, it is a small part of the total measured soil movement from wind erosion that is reported in the agricultural literature. Another method for evaluating control effectiveness is measuring the increased wind threshold velocity (i.e., the wind velocity required to suspend particles from the surface). Emissions decrease as wind threshold velocity increases for a given surface. Entrainment velocity, the windspeed required to entrain 10 g/min of particles, can be used to measure control effectiveness. These different measures of control efficiency are important to assess reported control efficiencies and to compare results of different investigators.

Control efficiencies are site specific and depend upon a myriad of variables that change with control types, emission sources, and climates. Even for a specific site, control efficiency may vary daily because of changes in the many variables affecting emissions. Another factor affecting control efficiency is the uncontrolled emission rate from which the efficiency is derived. The magnitude of uncontrolled emissions also varies across types of sources, and, for a given site, may vary daily depending on climate, surface of the source, and other factors. The major factors affecting control efficiency are summarized in Table 9.

7.1 SUMMARY OF CONTROL EFFICIENCY

This section summarizes control efficiencies in general terms based on published estimates and measurements in the form of ranges. When a single

TABLE 9. FACTORS AFFECTING CONTROL EFFICIENCY

1. Source: shape, size, composition, particle size distribution (e.g., percent silt), degree of compaction, surface moisture, and cohesiveness of particles.
2. Climate: windspeed, direction, and frequency; temperature; precipitation; and humidity.
3. External factors: vehicular activity (number, speed, weight, and number of wheels), physical disturbance (digging and animals), construction activity (excavating and loading onto or moving from the source), extent and type of vegetation, and active or inactive site.
4. Type of control:
    - A. Chemicals--product type; dilution rate; application rate, method, and frequency; time; and climate.
    - B. Vegetative covering--type, nutrients, extent of coverage, climate, and external activity.
    - C. Windscreens--height, distance, direction, porosity, design, features, and construction features (e.g., structural stability).

value is used for control efficiency, the reader should note the range of estimates from which it is derived and the potential for a higher or lower control efficiency for a specific case, depending upon specific site conditions. Control efficiencies for inhalable particles are presented when available.

Reported control efficiencies for unpaved roads are summarized in Table 10. Chemical stabilizers applied to unpaved roads have resulted in reported control efficiencies of 40 to 96 percent. The PEDCo study of coal mine haul roads, used by heavy-duty vehicles, reported control efficiencies of 40 to 60 percent over a 1-month period from mixed-in-place and topical applications of stabilizers. For unpaved roads used by light-duty and heavy-duty vehicles, more frequent stabilizer applications and measurements conducted shortly after application yielded higher control efficiencies. These data suggest that control efficiencies of about 50 percent can be achieved on haul roads used by heavy-duty vehicles from only monthly applications. These data also suggest that more frequent applications or applications on roads used by light- to medium-duty vehicles can achieve control efficiencies greater than 90 percent. Cowherd et al. (1982) reported that control efficiency decreased as the number of vehicles increased. They also reported no significant difference between control efficiencies for TSP's and for inhalable particles.

Wet suppression techniques for unpaved roads also provide a relatively wide range of control efficiencies, which appears to depend upon source and frequency of application. A control efficiency of about 50 percent is suggested for watering unpaved roads. Control efficiency is expected to increase with application frequency; i.e., extensive, frequent watering yields a control efficiency greater than 50 percent. The practicality of very frequent watering is governed by considerations of cost and water availability. Cowherd et al. (1982) reported that watering reduced inhalable particles more than it reduced total suspended particles (63 versus 50 percent reduction).

An aggregate cover for the road (e.g., gravel or slag) can provide 30 to 50 percent control, whereas paving the road can reduce emissions about 85 percent. The use of civil engineering fabrics or road carpet can reduce emissions from an unpaved road by about 45 percent. Drehmel and Daniel (1982) reported similar control efficiencies for total suspended and inhalable particles (44 and 43 percent, respectively) from the use of both road carpet and aggregate on an unpaved road.

Control efficiency data are also available for storage and waste piles, which have been investigated extensively in recent years for control of wind erosion and fugitive emissions. Data for chemical stabilization of coal storage piles and mineral waste tailings in Table 11 show control efficiencies of 75 to 100 percent. These data suggest that control efficiencies approaching 100 percent are achievable for inactive piles, while an efficiency of 75 to 90 percent from frequent applications may be more appropriate for an active pile. Control efficiency data for watering range from 25 to 90 percent control and are probably a function of source characteristics, climate, and application frequency.

TABLE 10. REPORTED CONTROL EFFICIENCIES FOR UNPAVED ROADS

Method	Efficiency, %	Notes	Reference(s)
Chemical stabilization	50		Jutze and Axetell, 1974; EPA, 1981, 1982a; PEDCo, 1977
	78-86	Arco coal mine study	Maxwell et al., 1982
	85	CO Department of Health	Tistinic, 1981
	90-95	MRI studies	Bohn et al., 1978; Cowherd et al., 1979a
	70-96	TRC study	Larson et al., 1981
	40-60	PEDCo study; 4-week average	Rosbury and Zimmer, 1983
(Lignosulfonate)	43(25-63)	4-week average	Rosbury and Zimmer, 1983
(Arco 2200®)	42(0-56)	1-week average	Rosbury and Zimmer, 1983
(Calcium chloride)	47 (20-82)	4-week average	Rosbury and Zimmer, 1983
(Bitumens®)	66 (49-79)	3-week average	Rosbury and Zimmer, 1983
(Coherex®)	94 (88-99)	4-week average	Russell and Caruso, 1983
(Lignosulfonate + Arcoat®)	89 (74-96)	4-week average	Russell and Caruso, 1983
(Oil well brine)	94 (91-99)	4-week average	Russell and Caruso, 1983
(Calcium chloride)	60		Levene and Drehmel, 1981
($CaCl_2$ + water)	95	PEDCo/MRI study	Axetell and Cowherd, 1981
(Oiling)	50-98		Levene and Drehmel, 1981
(Oiling)	70	CO Department of Health	Tistinic, 1981
(Oiling)	75	MRI study	Bohn et al., 1978
(Oiling)	85	Daily application; estimate	Morwald, 1983
Wet suppression	20-70		PEDCo, 1978
	50		PEDCo, 1977; Bohn et al., 1978
	25-50		Tistinic, 1981
	97-99	Water 2 to 4 times/h	Maxwell et al., 1982
	40		Levene and Drehmel, 1981
	45	Water once hourly	Rosbury and Zimmer, 1983
	55	Water twice hourly	Rosbury and Zimmer, 1983
	30-50	Water twice/day, with construction	EPA, 1982a
	42 (24-81)	4-week average, with surfactant	Rosbury and Zimmer, 1983
Physical covering			
Aggregate cover	50		EPA, 1982a; Tistinic, 1981
	30		Bohn et al., 1978
Paving	85		EPA, 1981; PEDCo, 1977
	80-90		Bohn et al., 1978
	99	With frequent cleaning	Tistinic, 1981
Road carpet	45		Tistinic, 1981; Levene and Drehmel, 1981

TABLE 11. REPORTED CONTROL EFFICIENCIES FOR STORAGE AND WASTE PILES

Method	Efficiency, %	Notes	Reference(s)
Chemical stabilization	85-93	Coal	Tistinic, 1981
	90	Coal	PEDCo, 1977
	up to 99	Coal	Bohn et al., 1978
	up to 100	Coal	Boscak and Tandon, 1974
	up to 94	Coal	Nguyen and Booth, 1980
	75	Tailings	Bohn and Johnson, 1983
	90+	Tailings (active area)	Bohn and Johnson, 1983
	80	Tailings (active area)	Jutze and Axetell, 1974; EPA 1982a
	95	Oil on coal, plus compaction	Morwald, 1983
Watering	25-50		Tistinic, 1981
	50		Jutze and Axetell, 1974; PEDCo, 1977
	80		Bohn et al., 1978
	90	Fixed spray with surfactants	Shrimpton and Shin, 1983
Windbreak	30-50		Tistinic, 1981
	30		Bohn et al., 1978
	up to 80		Levene and Drehmel, 1981
	75	TSP, active fly ash pile	Lawrence, 1983
	60	IP, active fly ash pile	Lawrence, 1983
Enclosure (mulch)	85		Tistinic, 1981
(slag).	90-99	Crude estimate	PEDCo, 1977
	100		EPA, 1982a; Bohn et al., 1978
(dome or cover)	up to 100		Vogel and O'Sullivan, 1983
	70-99	Loading onto pile	EPA, 1982a
	95-99	From wind erosion	EPA, 1982a
Vegetative stabilization	50-80		EPA, 1982a
	25	Arid conditions, sparse vegetation	EPA, 1982a
	up to 100	Dense vegetation	EPA, 1982a
	85-100	With chemical stabilization	EPA, 1982a
	65		Jutze and Axetell, 1974
	90	With chemical stabilization	Jutze and Axetell, 1974

Use of windscreens for storage piles has received attention by investigators who have studied the optimization of windscreen design and placement. Reported efficiencies range from 30 to 80 percent and indicate a slightly better control efficiency for total suspended particles than for inhalable particles (75 versus 60 percent from one study). Enclosure of the pile can result in 85 to 100 percent control, depending upon the type and extent of the cover. For active piles that cannot be completely enclosed, efficiencies are lower.

The control efficiency of vegetative stabilization depends upon the emission source, climate, and extent and type of vegetative cover. Efficiencies on the order of 25 percent can be expected in arid areas with sparse vegetation, whereas a dense vegetative cover may achieve efficiencies approaching 100 percent. A range of 50 to 80 percent is recommended for a typical vegetative cover. Combining vegetative stabilization with chemical stabilization or physical covering decreases wind erosion and improves control efficiency. These combined techniques can achieve a control efficiency of 85 to 100 percent.

These data on control efficiencies were applied to several types of TSDF's. Control efficiencies for various sources and controls are summarized in Table 12. Most of the control efficiency data were from tests of unpaved roads and waste or storage piles. Few data are available for relatively flat sources, such as landfills; however, control techniques have been demonstrated on croplands and for construction areas. Control efficiency for a relatively flat, inactive source should be at least as high as that for an inactive waste pile. For relatively flat, active sources, control efficiency is expected to be similar to that observed for active waste or storage piles and unpaved roads.

Control efficiencies for inhalable particles are not presented separately in Table 12 because few data are available. For chemical stabilizers, Cowherd et al. (1982) found that control efficiencies for inhalable and total suspended particles were similar. When applications are sufficiently frequent, this observation appears reasonable because both large and small particles are bound together or covered by a thin film.

Cowherd also reported that wet suppression by watering reduced inhalable particles from unpaved roads by 63 percent compared to a 50-percent reduction in total suspended particles. This observation is also plausible if small particles are agglomerated at a higher rate than are larger particles. For wet suppression, a 10- to 15-percent increase is recommended for inhalable particle control from control efficiency for total suspended particles.

An impermeable cover should cover both large and small particles; therefore, the same control efficiency is recommended for both. For road carpet, the same control efficiency was observed for both total suspended and inhalable particles (43 to 44 percent).

Windscreens function by increasing effective threshold velocity and are thus expected to be more efficient for larger particles, which have a

TABLE 12. SUMMARY OF ESTIMATED CONTROL EFFICIENCY PERCENTAGES

Source	Chemical stabilization[a]	Wet suppression[b]	Physical cover[c]	Vegetative cover	Vegetative with physical or chemical stabilization	Wind-screen[d]	Vehicle speed reduction
Active landfills, drum storage	75-90	25-90	<85	NA[e]	NA	30-80	NA
Active waste piles	75-90	25-90	<85	NA	NA	30-80	NA
Unpaved, contaminated roads	40-96[f]	50	30-85[g]	NA	NA	NA	25-80[h]
Closed landfills, lagoons, and impoundments	75-100	25-90	85-100	50-80[i]	85-100	30-80	NA
Inactive waste piles	75-100	25-90	85-100	50-80[i]	85-100	30-80	NA

[a] Reductions in inhalable and total suspended particles are similar.

[b] Watering reduces inhalable particles slightly more than it reduces total suspended particles.

[c] Reductions for road carpet were the same for total suspended and inhalable particles.

[d] Reductions were greater for total suspended particles than for inhalable particles.

[e] NA = not applicable.

[f] An efficiency of over 90 percent appears to be achievable.

[g] 30 percent for gravel, 45 percent for road carpet, and 85 percent for paving.

[h] Based on reductions from an initial speed of 64 km/h (40 mph).

[i] Can approach 100 percent for dense vegetative cover.

higher threshold velocity, than for smaller particles. One test indicates that control efficiency for total particles is about 15 percent greater than for inhalable particles. No data are available for vegetative covers; however, the soil-binding effects of plants and the wind-sheltering effect of the vegetative cover suggest that control of total particles is better than control of inhalable particles. Speed reduction is also likely to reduce total suspended particles more than it reduces inhalable particles.

7.2 APPLICABILITY AND PRACTICALITY OF CONTROLS FOR TSDF's

Several types of TSDF's with potential for fugitive particulate emissions are candidates for application of control techniques discussed in this section. These facilities include landfills, dried lagoons or closed surface impoundments, soil around drum storage or disposal areas, contaminated roads, and contaminated waste piles. Controls for unpaved roads (e.g., mine haul roads, plant roads, and public roads) and for piles (e.g., storage and waste piles) have been tested and demonstrated. Application of controls to agricultural sources (e.g., flat fields and croplands), in addition to successful application to piles with higher erosion potential, indicates that relatively flat area sources (e.g., landfills and lagoons) also can be controlled effectively by these techniques.

Choosing practical control options for an active site requires knowledge of operating characteristics, emission sources to be controlled, and degree of control required. Control options for inactive sites also apply to inactive portions of an operating site. Therefore, closed cells of a landfill or completed waste piles at active sites are candidates for chemical stabilization, vegetative stabilization, or physical covering. However, these control techniques may be destroyed if applied to the active portion of an operating site. Chemical stabilization or physical covering could provide some unknown degree of emission control for an active area. However, their practicability may be site specific, depending upon the required frequency of stabilizer application or labor for placing/removing covers, control efficiency needed, and control efficiency that could be obtained.

As with control efficiency, the practicality of a given control technique for a specific site may depend upon the site's characteristics, required degree of control, and ultimately cost assessment associated with control and environmental and health protection gained.

Chemical stabilization has been demonstrated as a practical emission control option applicable to each type of TSDF. The stabilizers are usually sprayed, which is a simple technique that covers the source uniformly. However, the different types of chemicals offer different advantages and disadvantages that may make one type of chemical stabilizer more or less practical than another. For example, although deliquescent salts pull moisture from the air and suppress dust, these salts are water soluble and not suitable for areas with high levels of rainfall. They can be leached from the source and may kill adjacent vegetation. Chloride salts may also pose a corrosion problem for equipment operating on or near the source. Similarly, lignosulfonates are excellent binders but are also water soluble with disadvantages similar to salts in wet areas. These facts imply that salts and lignosulfonates may be practical control options for relatively dry areas and impractical for areas with a high incidence of rainfall.

Courtney (1983) examined meteorological data to determine where dust suppressants strongly affected by rainfall are practical. He listed the 10 driest (most suitable) States by decreasing dryness as California, Montana, Nevada, New Mexico, Colorado, Wyoming, Arizona, Utah, Oregon, and Idaho. The 10 wettest (most unsuitable) States by decreasing wetness are Alabama, Mississippi, Arkansas, New Hampshire, Kentucky, Georgia, Missouri, Tennessee, Louisiana, and South Carolina.

The efficiency of other chemical stabilizers, such as elastomeric or latex polymers and asphalt emulsions, is also influenced by rainfall, but to a lesser extent than the water-soluble stabilizers. These types of stabilizers may be more suitable for areas with relatively high levels of rainfall.

Oiling is a demonstrated, generally practical, and effective control option for various types of emission sources. However, several factors for a specific site may make it an impractical control option: oil availability; potential for contaminants in the oil, runoff, leachate generation, or solubilization of contaminants from the soil; increased hydrocarbon emissions; and cost. Potential environmental effects of used oil are unknown--EPA has issued an advisory circular warning of resultant skin cancer in laboratory mice from used oil.

In general, chemical stabilization appears to be a practical control option for most types of sites, although a particular type of chemical stabilizer may be more suitable than the others for a specific site.

Wet suppression techniques, such as spraying with water, are a demonstrated control option that may be practical for some emission sources. For example, fixed sprays on coal storage piles, watering of construction areas, and wetting of unpaved roads have been used routinely in the past. Application of the suppressant by spraying is simple and covers the source uniformly. Wet suppression techniques are potentially applicable to all types of TSDF's.

Wet suppression may be impractical in extremely dry areas with little available water or in arid areas requiring frequent or continuous application to maintain effectiveness. Watering of contaminated soil may spread the contaminants to adjacent soil, increase leachate generation, or contaminate surface water. Wet suppression methods may also be impractical when a high level of continuous emission control is desired. Wet suppression techniques have a short-lived effectiveness estimated at about 50 percent for unpaved roads. Surfactants can be used to extend water and to improve surface wetting. If surfactants are used on contaminated soil, the user should consider the potential for enhanced solubility of organics in the liquid phase and the spread of contaminants to uncontaminated soil or water.

Physical covering of the emission source is a practical control option most effective for inactive sites. For example, old landfills, lagoons, and waste piles can be covered completely with a compacted clay cap, soil, slag, or synthetic cover that essentially eliminates fugitive particulate emissions. For active sites, partial or daily covers can be used to minimize emissions; however, corresponding control efficiency is lower than that of a complete cover. Covers also have been used on unpaved roads in the form of road carpet, gravel, or paving. Physical covering is a demonstrated control technique in which practicality is governed by type of cover and its cost. The type of cover for a specific site must be selected considering local availability of cover materials, site characteristics such as shape and size, active or inactive use, and desired control level.

Vegetative covers have been demonstrated as a practical control option for fields, croplands, and waste piles. For TSDF's, vegetative covers are a practical option for inactive sites; however, disruption and damage to the vegetative covers make them impractical for active sites. Vegetative covers have been recommended for the final cover of closed landfills, lagoons, and impoundments to minimize water erosion and infiltration through the cap. Wind erosion control is an additional benefit. Vegetative stabilization coupled with either chemical stabilization or physical covering is also a practical and more efficient control option.

Vegetative covers are obviously impractical for roads and facilities undergoing construction and for sources that cannot support plant life because of salts, heavy metals, or other site-specific characteristics affecting germination and growth. In arid areas, the vegetative covering may be too sparse to be effective and practical. Another consideration is the potential for uptake of contaminants by plants and potential for distribution of contaminants through the food chain.

Windscreens have been used to decrease wind erosion and may be a practical control option for some sites, with successful use demonstrated for flat fields and conical storage piles. A disadvantage is that their control efficiency is limited and may be unacceptably low for a source requiring a high degree of control. Windscreens may be impractical for very large area sources and very high conical sources because of the size required and potential construction and stability problems.

Vehicle speed reduction can be a practical control option for unpaved, contaminated public roads or access roads. As a control option, speed reduction alone may not be sufficient because of its low control efficiency. However, speed reduction coupled with another control option may be a low-cost and practical means to further decrease particulate emissions.

7.3 COST ESTIMATES FOR CONTROL TECHNIQUES

This section summarizes cost estimates for the control techniques discussed in the preceding sections. The most reliable cost estimates in the literature are probably those describing a technique that actually has been applied and evaluated for a specific site. Estimates for sites derived by chance may not account for all site-specific features that could significantly affect costs.

One factor affecting costs is the operator's decision either to purchase or rent the necessary capital equipment. For example, a permanent site such as an iron and steel plant may choose to install storage tanks for chemical stabilizers because of frequent applications and high-volume use of the stabilizer. Other sites that require infrequent applications, such as monthly spraying of waste piles, may find it more economical to use drum storage and rented equipment.

Site preparation (e.g., regrading and compaction), accessibility, and size can also significantly affect costs. Other cost factors include extent of monitoring and maintenance required, expected life of the control and site, interest rates, location, climate, and choice of product and supplier for a given control technique. Some of these variations are represented by a range of costs provided in the following sections of general discussion.

The cost information provided in this section is based primarily on 1983 to 1984 dollars. The date associated with the reference generally provides the year in which cost estimates or data were derived.

Chemical stabilization techniques have been used widely on unpaved roads, waste piles, and croplands; consequently, information is available in the literature on material costs, dilution ratios, application rates, and application costs. For TSDF's, the cost analysis concentrates on annual costs. A large source that requires frequent applications may choose to invest capital to save on long-term rental charges. For example, an integrated iron and steel plant invested $100,000 (installed cost in 1980) in a distribution truck and storage tanks to control emissions from unpaved plant roads (Cowherd et al., 1982). In 1980, the extent of treatment was 1,630 miles with an annual operating and maintenance cost of $287,000. For smaller sources that require applications less frequently than on unpaved roads, monthly equipment rental and drum storage may be a more economical alternative. For example, inactive waste piles may require only monthly or less frequent applications. Other TSDF's may have a limited operating life, which also affects the choice of equipment purchases or rental. The cost analysis for waste piles and area sources focuses primarily on annual costs and equipment rental because of the expected characteristics of limited size, finite operating life, and relatively infrequent applications (compared to unpaved roads).

Basic costs for chemical stabilization include the chemical's material and shipping costs, spray equipment rental, and labor for application. Rosbury (1984) compiled a list of various stabilizers, recommended dilution and application rates, and recommended material costs. Based upon these recommended application rates and costs, material costs per unit of source area were derived in Table 13.

TABLE 13. MATERIAL COSTS FOR CHEMICAL STABILIZERS
(Rosbury, 1984)

Type	$\$/m^2$	$\$/yd^2$	Typical stabilizers
Bitumens	0.026-0.094	0.022-0.078	Coherex®, Docal 1002®, Petro Tac P®
	0.20-0.80	0.17-0.67	AMS 2200®, Peneprime®, Resinex®, Retain®
Adhesives	0.012-0.12	0.01-0.10	Acrylic DLR-MS®, Biocat 300®, Cunasol AK®, DCL-1801®, Dust Bond 100®, Orzan®, Soil Sement®, Terra Tac®, Weslig 120®
	0.12-0.82	0.10-0.68	CPB-12®, Dust Ban®, Dustbinder 124®, Rezosol 5411-B®, SP-301®, Soil Gard®, Soiltex®, Suferm®
Lignosulfonates	0.017-0.025	0.014-0.021	Flambinder®, Lignosite®, Woodchem LS®
Salts	0.06-0.13	0.05-0.11	$CaCl_2$, $MgCl_2$

TABLE 14. RENTAL COST FOR SPRAY EQUIPMENT
(Means, 1984)

Description	Rental cost (\$/day)[a]
Emulsion sprayer, 65 gal, 5-hp engine	17
Emulsion sprayer, 200 gal, 5-hp engine	34
Water tank truck, engine-driven discharge, 5,000 gal	225
Water tank truck, engine-driven discharge, 10,000 gal	325

[a] Includes overhead, profit, and operating cost (excluding labor).

Costs in Table 13 reflect the wide range in material costs. Approximately 20 products listed by Rosbury cost $\$0.012/m^2$ to $\$0.12/m^2$, and about 13 products cost $\$0.12/m^2$ to $\$0.82/m^2$. The material cost of bitumens, lignosulfonates, and salts, which are demonstrated fugitive dust controls, cost $\$0.02/m^2$ to about $\$0.13/m^2$ per application.

Costs for equipment rental and labor were obtained from Means's Building Construction Cost Data (1984). For topical application of the stabilizer, some type of spray equipment is required. The size of the site to be stabilized dictates in part the required capacity of the spray equipment. For example, a waste pile with 0.1 acre of exposed surface requires about 242 gallons of Coherex® solution, whereas a 100-acre site could require 242,000 gallons of the solution (at an application rate of 0.5 gal/yd^2). Some typical rental costs for spray equipment are given in Table 14.

Labor costs cited in Means (1984) are $21.95/h for common building laborers and $22.60/h for truck drivers, including fringe benefits, overhead, and profit. The labor required depends strongly on the site's size and the quantity of stabilizer to be applied. An example cost estimate is provided in Table 15 for two sites ranging in size from 0.1 to 100 acres. An estimated material cost of $\$0.13/m^2$ is used and was obtained from the range discussed for stabilizers ($\$0.02/m^2$ to $\$0.13/m^2$, excluding shipping). For the 0.1-acre site, it was assumed that one person would be required for 1 day to apply the stabilizer. A significant portion of this person's time would be in equipment preparation and cleanup, in addition to spraying. For larger sites, larger equipment can be used with the advantage of saving on labor costs. Li et al. (1983) estimated that a 100-acre site could be sprayed by a single operator in an 8-hour period. However, it was not clear whether his estimate included loading and mixing time. The example in Table 15 assumes that two persons, one truck driver and one spray operator, would be required with a total of about 8 hours for spraying and about 8 hours for filling the tank truck several times. For the small site application costs are labor intensive, while material cost dominates large applications. This example illustrates the site-specific nature of the costs and implies that the choice of stabilizer and its cost most significantly affect total application cost for a large site.

Estimates in Table 15 are crude and do not account for site-specific factors that may increase total costs. Cost estimates were provided by Bohn and Johnson (1983) for stabilizing active waste piles and are given in Table 16 along with estimates from other sources for comparison. Bohn and Johnson performed emission testing at the Minnesota site and, because of their direct knowledge of the site's characteristics, their cost estimate should be more accurate for the site than for the example. Their estimates are also useful because a control efficiency is associated with each cost. For 90+ percent control, Bohn and Johnson's estimate yields a cost per application of $111/acre to $230/acre for latex, $93/acre to $225/acre for lignosulfonate, $159/acre to $227/acre for petroleum resin, and $525/acre to $1,590/acre for magnesium chloride. Bohn and Johnson's estimates were for a 3-month period when wind erosion is greatest and were converted to an annual basis by multiplying by 4. Because less frequent applications may

TABLE 15. EXAMPLE OF STABILIZER COSTS

Cost element		Estimated cost per application[a] 0.1 acre	Estimated cost per application[a] 100 acres
Material cost: \$0.13/m^2		53	53,000
Labor: 8 h @ \$23/h		184	--
32 h @ \$23/h		--	736
Equipment: (200 gal) \$34/day for 1 day[b]		34	--
(10,000 gal) \$325/day for 2 days		--	650
	Total, \$	271	54,400
	\$/m^2	0.67	0.13
	\$/acre	2,710	544

[a] 1 acre = 4,047 m^2.

[b] 1 day minimum for rental.

TABLE 16. COSTS FOR CHEMICAL STABILIZATION

Type	Cost, $	Units	Notes	Applications	Reference
Petroleum resin	1,700-2,040	acre/yr	75 percent control for waste piles in MN	8-12	Bohn and Johnson, 1983
	2,540-2,720	acre/yr	90+ percent control for waste piles in MN	12-16	Bohn and Johnson, 1983
Lignosulfonate	520-744	acre/yr	75 percent control for waste piles in MN	8	Bohn and Johnson, 1983
	1,120-1,800	acre/yr	75 percent control for waste piles in UT/WY	8	Bohn and Johnson, 1983
	744-780	acre/yr	90+ percent control for waste piles in MN	8-12	Bohn and Johnson, 1983
	1,680-1,800	acre/yr	90+ percent control for waste piles in UT/WY	8-12	Bohn and Johnson, 1983
Latex	888-1,840	acre/yr	90+ percent control for waste piles in MN	8	Bohn and Johnson, 1983
Magnesium chloride	12,700	acre/yr	90+ percent control for waste piles in MN	8	Bohn and Johnson, 1983
	4,200	acre/yr	90+ percent control for waste piles in UT/WY	8	Bohn and Johnson, 1983
Coherex®	547	acre/application	Based on 100-acre site	1	Li et al., 1983
Chemical stabilizer	71-1,430	acre/application	Based on 0.07-acre site	1	Vogel and O'Sullivan, 1983
Salts	242-532	acre/application	Material cost only, excluding shipping	1	Rosbury, 1984
Bitumens	106-378	acre/application	Material cost only, excluding shipping	1	Rosbury, 1984
	823-3,240	acre/application	Material cost only, excluding shipping	1	Rosbury, 1984
Lignosulfonates	68-102	acre/application	Material cost only, excluding shipping	1	Rosbury, 1984
Adhesives	48-480	acre/application	Material cost only, excluding shipping	1	Rosbury, 1984
	480-3,290	acre/application	Material cost only, excluding shipping	1	Rosbury, 1984

be required for the other 9 months, costs in Table 16 may be somewhat overstated on an annual basis.

Physical covers such as synthetic materials, soil, slag, or mulch can be placed over the fugitive emission source as a dust control. Costs from the literature are summarized in Table 17. Most of the synthetic covers listed by Rosbury include only the material cost and range from $\$0.90/m^2$ to $\$5.40/m^2$. The cost of installation labor (including fringe benefits and overhead) is estimated by Means (1984) as about $\$0.26/m^2$; however, this cost does not account for any site-specific problems (e.g., accessibility or source shape) that may increase labor costs. Data provided by Rosbury (1984), Means (1984), and Li et al. (1983) indicate that simple installation of a synthetic cover ranges from about $\$1/m^2$ to $\$6/m^2$.

Vogel and O'Sullivan's (1983) estimate of $\$13/m^2$ to $\$32/m^2$ for a synthetic cover was derived for covering the liquid surface of a surface impoundment. The higher installed costs (compared to the other references) are due to seam sealing with adhesives instead of thermal sealing, use of a thick membrane, and use of a lining membrane as well as a cover membrane. This study was more concerned with control of volatile vapor emissions than with fugitive particulate emissions.

The estimate of $\$43/m^2$ to $\$65/m^2$ from Vogel and O'Sullivan was for a synthetic cover over an active waste pile. Tension cables are used for support and allow the pile to be in active use. In addition, an auger feed system is used to place wastes on the pile under the cover or to remove wastes from the covered pile. Vogel's estimate for a dome includes construction of a structure, similar to those used by highway departments for storage of salt, that would cover an entire waste pile.

The foam system listed in Table 17 is a urea-methylene complex that is applied as a liquid that dries and hardens. Vogel and O'Sullivan (1983) stated that the foam would provide an effective dust cover and could be used on parts of an active landfill. Material and application labor cost was estimated as $\$2.15/m^2$. Equipment for applying the foam costs around $4,000.

Estimates for a soil cover provided by Li et al. and by Vogel and O'Sullivan differ, with Vogel's 1-inch cover costing about the same as Li's 6-inch cover. Cost data from Means (1984) were used to generate another estimate for comparison and indicate that Vogel's higher estimates are probably more accurate. For example, the equivalent of about 2 in. of soil is required to obtain a minimum 1-in. thickness after grading (at the thinnest point) and would require 269 yd^3/acre. For locally available material that is moved 1,000 to 2,000 ft by a self-propelled scraper, the cost is $\$1.15/yd^3$ to $\$1.43/yd^3$ or a total of $309/acre to $384/acre (Means, 1984). For locally purchased material hauled 2 to 5 mi by truck, total cost is $\$4.91/yd^3$ to $\$6.36/yd^3$ or $1,320/acre to $1,700/acre (Means, 1984).

Capital costs, listed in Table 17, must be annualized over the life of the control technique and added to annual operating costs to determine

TABLE 17. COSTS FOR COVERS

Type	Cost, $	Unit	Notes	Reference
Enviromat®	5.40	m^2	Material cost only	Rosbury, 1984
Gagle® liner	4.80-6.00	m^2	Includes installation	Rosbury, 1984
Mirafi® fabrics	1.08-1.44	m^2	Material cost only	Rosbury, 1984
Supac 5NP (UV)®	0.90	m^2	Material cost only	Rosbury, 1984
Jute mesh	1.02	m^2	Includes overhead, profit, and installation	Means, 1984
Plastic netting	0.66	m^2	Includes overhead, profit, and installation	Means, 1984
Polypropylene mesh	2.24	m^2	Includes overhead, profit, and installation	Means, 1984
Enkamat®	4.20	m^2	Material cost only	Li et al., 1983
Polypropylene	0.36	m^2	Material cost only	Li et al., 1983
Curlex® blanket	0.60	m^2	Material cost only	Li et al., 1983
Foam (hardened)	2.15	m^2	2-inch layer, material plus labor, add $4,000 for equipment	Vogel, 1983
Synthetic cover	43-65	m^2	Includes installation, tension cables, auger feed system	Vogel, 1983
	13-32	m^2	Includes installation of simple cover only	Vogel, 1983
Dome cover	46,000	each	Installed, 50-foot diameter, 664-ton capacity	Vogel, 1983
	80,000	each	Installed, 100-foot diameter, 4,650-ton capacity	Vogel, 1983
Soil cover	361	acre	6-inch soil cover, local material	Li et al., 1983
	380	acre	1-inch cover, local material	Vogel, 1983
	2,260	acre	1-inch cover, purchased soil	Vogel, 1983
	1,500	acre	6-inch cover, local soil	Vogel, 1983
	9,100	acre	6-inch cover, purchased soil	Vogel, 1983
Mulch cover	800	acre		Rosbury, 1984
Slag cover	57-73	acre	Locally available	EPA, 1982b
	156-168	acre	Transported	EPA, 1982b

total annualized control cost. Very few data are available for the expected lifetime of these controls. For synthetic covers, Li et al. (1983) used an estimated lifetime of 5 years. Operating costs are also difficult to determine and include repairs, inspection, and general maintenance. Li et al. (1983) estimated 1 person-shift per month for inspection, data collection, and minor repairs. Example cases are given in Table 18 based on assumptions of 5-year and 10-year lifetimes and an interest rate of 10 percent. Depending upon the cover life, the sophistication of the cover system, and whether in active or inactive use, costs in the example range from about \$4,000/yr to \$37,000/yr.

Costs for vegetative stabilization depend strongly upon site preparation requirements and seeding method. Typical costs are provided in Table 19. For a site that requires fine grading, the cost is about \$1.67/m^2 or \$6,800/acre. For large areas that support vegetation and require no fine grading, hydraulic seeding can be used at a cost of \$0.38/m^2 to \$0.44/m^2 or \$1,500/acre to \$1,800/acre. Aerial seeding of large sites offers the lowest cost application at \$430/acre to \$715/acre. For a site that requires topsoil to establish vegetation, costs in Table 19 indicate that removing topsoil from a nearby site and spreading it could add \$5.45/m^3 for the topsoil, or about \$0.55/m^2 for a 4-in. (0.1-m) layer. Purchased topsoil increases the cost by \$1.88/m^2.

Some example costs for vegetative stabilization are given in Table 20. Annual operating costs for a site after the vegetation has been established are expected to be small. Some sites may require periodic maintenance, such as water erosion control, reseeding, or adding fertilizer. Initial capital costs must be annualized over the expected life of the vegetative cover or the life of the site, whichever is shorter. These annualized capital costs are added to the annual operating costs to determine total annualized cost. Operating costs are determined by the specific site's requirements and should be estimated based on knowledge of site characteristics and degree of monitoring and maintenance expected for a particular vegetative cover at a particular site.

Windscreens placed around a source or perpendicular to the direction of the prevailing wind decrease the wind velocity behind the screen and reduce fugitive emissions. The major cost associated with windscreens is the initial installed capital cost. Few data are available for the expected lifetime of the screen, which can significantly affect the estimate of annualized cost. Li et al. (1983) used an estimated lifetime of 10 years, which is assumed in this analysis.

Some typical costs for windscreens are provided in Table 21. Rosbury's costs represent material costs only, whereas Vogel's costs include installation. For comparison, installation costs were extracted from Means (1984) for chain link fence (2 to 3 meters high) with a range of about \$7 to \$12 per linear meter. Adding this installation cost to Rosbury's range of material cost yields an installed cost range of \$14 to \$22 per linear meter for a 2-meter-high fence. Vogel's estimate is about twice this derived cost and can be attributed to a higher material cost (about \$22 per linear

TABLE 18. EXAMPLE COSTS FOR SYNTHETIC COVERS

Case 1 Inactive waste pile, area = 2,023 m^2 (0.5 acre).
Assume operating cost is 8 h/mo for inspection; minor repairs at \$23/h = \$2,200/yr.

Installed capital cost = \$6/m^2 = \$12,100.
Annualized cost of capital (5-yr life) = \$3,190 (@ 10%).
Annualized cost of capital (10-yr life) = \$1,970 (@ 10%).

Annual cost[a] (5-yr life) = \$5,390/yr = \$2.66/m^2/yr.
Annual cost[a] (10-yr life) = \$4,170/yr = \$2.06/m^2/yr.

Case 2 Active waste pile, area = 2,023 m^2 (0.5 acre).
Use \$2,200/yr for operating cost above the usual operating cost of an active waste pile. Cover with synthetic cover, tension cables, and install an auger feed system at \$43/m^2 to \$65/m^2.

Capital cost = \$87,000 to \$131,000.
Annualized cost of capital (5-yr life) = \$23,000 to \$34,600.
Annualized cost of capital (10-yr life) = \$14,200 to \$21,401.
Annualized cost of capital (20-yr life) = \$10,200 to \$15,400.

Annual cost[a] (5-yr life) = \$25,200 to \$36,800/yr.
Annual cost[a] (10-yr life) = \$16,400 to \$23,600/yr.
Annual cost[a] (20-yr life) = \$12,400 to \$17,600/yr.

[a] Includes annual operating costs.

TABLE 19. COSTS FOR VEGETATIVE STABILIZATION
(Means, 1984)

Item	Total cost[a]
Fine grading and seeding, including lime, fertilizer, seed, and equipment	\$1.67/m²
Hydraulic seeding for large areas, including seed and fertilizer	\$0.38/m²
Hydraulic seeding described above plus wood fiber mulch	\$0.44/m²
Aerial operations, seeding only	\$430/acre
Aerial operations, seed and liquid fertilizer	\$715/acre
Remove and stockpile topsoil	\$1.49/m³
Spread topsoil from pile	\$3.96/m³
Furnish and place topsoil, 4 in. deep	\$1.88/m²

[a] Includes materials, equipment, labor, overhead, and profit.

TABLE 20. EXAMPLES OF SEEDING COSTS
(Means, 1984)

Case 1	Grade and seed 405 m² (0.1 acre) at \$1.67/m². Total cost = \$676
	For 4 in. of local topsoil, add \$0.55/m². Total cost = \$900
Case 2	Seed and fertilize 1-acre waste pile by hydraulic seeding. Include wood fiber mulch. Total cost = \$0.44/m² = \$1,800
Case 3	Aerial seeding, with fertilizer, of 100-acre site. Total cost = \$715/acre = \$71,500

TABLE 21. COSTS FOR WINDSCREENS

Item	Cost	Reference
Dusttamer® windscreen	\$6.80 to \$9.70/linear meter (material only)	Rosbury, 1984
Polyester windscreen	\$42.70/linear meter installed[a] (height = 1.8 m)	Vogel and O'Sullivan, 1983
Polyester windscreen	\$21.50/m² to \$26.90/m² total area, installed[a]	Vogel and O'Sullivan, 1983
Polyester windscreen	\$4,000 for 3-m fence around 0.07-acre pile	Vogel and O'Sullivan, 1983
Polyester windscreen	\$10.76/m² (material cost only)	Vogel, 1984
Annualized cost, windscreen	\$300/acre/yr (100-acre site, 10-yr life)	Li et al., 1983
Fence installation[b]	\$7.15/linear meter (height = 2 m, industrial chain link)	Means, 1984
	\$11.70/linear meter (height = 3 m, residential chain link)	Means, 1984

[a] Includes mounting hardware, post erection, and installation.

[b] Excludes material cost.

meter for a 2-meter height vs. about $10 per linear meter from Rosbury) and an installation cost about twice that derived from Means (1984). Obviously, the choice of materials and site-specific installation costs can significantly affect total installed cost.

Vogel and O'Sullivan (1983) estimated that the installed capital cost for a 3-meter windscreen around a small waste pile (0.07 acre) would be $4,000. For a 10-yr lifetime and a 10-percent interest rate, annualized capital cost is $652/yr. Assuming operating costs are 8 h/mo in labor at $23/h, total annualized cost for this site would be about $2,900/yr.

Wet suppression techniques use water or water plus a surfactant and frequent applications to achieve fugitive dust control. The cost of this technique depends upon the availability of water at the site and the type of application system used. An estimate for site access roads receiving 4 L/m^2 of water daily is $365/acre-yr (EPA, 1982b). Li et al. (1983) estimated the cost for watering a 100-acre waste pile in Wyoming as $942/acre-yr. Rosbury (1983) estimated the cost of watering haul roads to be $95/h. He assumed that wetting a 1-mi section of 50-ft wide road required 0.15 h (9 min). This yields a cost of $14.25/mi per application or, on an area basis, $2.35/acre per application. For an area source with no traffic, watering once or twice per day on 270 dry days during the year would cost $635/acre-yr to $1,270/acre-yr.

For a site with a projected life of several years, the operator may choose to install a permanent sprinkler system. These costs are listed in Table 22 and are total installed capital costs. An automatic sprinkler system, including pump, for a 1-acre (4,047-m^2) site costs about $11,000. If the operator does not have a source of water available and must dig a well 30 to 55 meters deep, the well and pump installation cost on the order of $2,300 to $4,600.

Control costs for fugitive emissions from unpaved roads have been reported in the literature by several investigators and are summarized in Table 23. These estimates are likely to be more representative of true costs than a crude estimate would be because actual sites, controls, efficiency, and costs were evaluated on a site-specific basis.

Rosbury (1983) investigated dust control on coal mine haul roads used by heavy duty equipment. For a 50-percent control from monthly applications, he estimated a cost of $7[illegible],000/mi-yr to $107,000/mi-yr for adhesive stabilizers and about $50,000/mi-yr for topical applications of salt. In contrast, estimates derived from tests conducted by Cowherd et al. (1982) and Russell and Caruso (1983) predict about 90 percent control from a Coherex® solution applied more frequently to unpaved roads in iron and steel plants. The derived costs of $43,000/mi-yr to $65,000/mi-yr are slightly lower than Rosbury's cost and have a higher estimated control efficiency (probably due to differences in traffic count, vehicle weight, speed, and road width).

Cost estimates for calcium chloride from State highway departments are also lower than Rosbury's estimate, with a range of $20,800/mi-yr to $38,100/

TABLE 22. COSTS FOR WET SUPPRESSION SYSTEMS

1. Sprinkler system (King, 1983): heavy-duty system, 18 to 28 m^2 covered per head, polyvinyl chloride (PVC) pipe and fittings, including trenching, overhead, and profit

Area covered (m^2)	\$/m^2
Less than 465	2.58
465 to 929	2.26
Over 929	2.10

- Add 25 percent for automatic system
- Sprinkler pump (Means, 1984) 37 to 68 gal/min, 15-ft lift, add \$305 to \$605

2. Wells (Means, 1984)

Well installation, drilled and cased (4- to 6-in. diameter)	\$46.60/m
(8-in. diameter)	\$59.90/m

Well pumps:	well depth to 100 ft, 144/gal/h to 1,110 gal/h	\$895 to \$995
	well depth to 180 ft, 102/gal/h to 1,356 gal/h	\$1,325

- Above includes material, installation, overhead, and profit

3. Water truck rental (Means, 1984)

Engine-driven discharge, 5,000 gal	\$225/day
Engine-driven discharge, 10,000 gal	\$325/day

TABLE 23. COSTS OF CONTROLS FOR UNPAVED ROADS

Type	Cost, $	Unit	Notes	Applications	Reference
Salt, mixed	102,000	mi/yr	50 percent control, heavy-duty traffic, coal mine in East	12	Rosbury and Zimmer, 1983
Salt, topical	49,800	mi/yr	50 percent control, heavy-duty traffic, coal mine in West	12	Rosbury and Zimmer, 1983
Adhesive	70,000	mi/yr	50 percent control, heavy-duty traffic, coal mine in East	12	Rosbury and Zimmer, 1983
Adhesive	107,000	mi/yr	50 percent control, heavy-duty traffic, coal mine in West	12	Rosbury and Zimmer, 1983
PS-300® oil	3,200	mi/application		1	Cooper et al., 1979
Standard® Dust oil	4,600-9,500	mi/application		1	Cooper et al., 1979
Oil	5,950	mi/application		1	Cooper et al., 1979
Emulsified asphalt	2,000	mi/application		1	Cooper et al., 1979
Oil	10,700	mi/yr	Includes annual road maintenance	-	EPA, 1982b
Calcium chloride	20,800	mi/yr	For roads in North Dakota	-	Cooper et al., 1979
	38,100	mi/yr	For roads in Virginia	-	Cooper et al., 1979
Coherex®	43,000	mi/yr	Steel plant roads, light-duty traffic, 90 percent control	230	Cowherd et al., 1982[a]
Coherex®	65,000	mi/yr	88 to 99 percent (average 91 percent) control, steel plant road	12	Russell and Caruso, 1983[a]
Watering	108,000	mi/yr	50 percent control, heavy-duty coal mine traffic	6,240	Rosbury and Zimmer, 1983
	41,400	mi/yr	In West Virginia	Dry days	Cooper et al., 1979
	62,800	mi/yr	In Arizona	Dry days	Cooper et al., 1979
	14.25	mi/application	0.15 h to water 1 mi at cost of $95/h	1	Rosbury and Zimmer, 1983
Gravel	5,000-9,200	mi/yr	Assumes 5-yr life, 10 percent interest, 25-ft width	1	Means, 1984[a]
Paving	13,000-17,000	mi/yr	Assumes 10- to 20-yr life, 10 percent interest, 25-ft width	1	Means, 1984[a]
Road carpet	9,700	mi/yr	43 percent control, includes aggregate on carpet	1	Levene and Drehmel, 1981[a]

[a] Derived from information contained in the reference.

mi-yr. Similarly, watering unpaved State roads costs \$41,000/mi-yr to \$63,000/mi-yr compared to Rosbury's estimate of \$108,000/mi-yr. Note the high frequency of watering required for the coal mine haul roads used by heavy-duty vehicles in Rosbury's estimate. The cost of oil for dust control ranges from \$2,000/mi to \$9,500/mi per application. Assuming monthly applications are required, associated annual costs for oiling are \$24,000/mi-yr to \$114,000/mi-yr.

Paving can reduce emissions from unpaved roads by 85 percent or more. The basic cost elements (Means, 1984) are preparation and rolling of the sub-base (\$0.74/yd^2), fine grading of the area to be paved (\$0.43/yd^2), and 3 in. of bituminous paving (\$6.15/yd^2) for a total installed capital cost of \$7.32/yd^2. For a road width of 25 ft, the capital cost is about \$107,000/mi. Assuming a lifetime of 10 years and an interest rate of 10 percent (capital recovery factor = 0.163), the annualized cost of the capital investment is \$17,400/mi-yr. For a 20-yr lifetime, the annualized cost of the capital is about \$13,000/mi-yr.

Adding gravel or other aggregate material to the dusty road surface also reduces fugitive emissions. Costs for adding gravel (material plus installation) range from \$1.31/yd^2 for 3 in. to \$2.37/yd^2 for 6 in. (Means, 1984). Total installed capital cost, excluding surface preparation, ranges from \$19,000/mi to \$35,000/mi for a 25-ft-wide road. Based upon a lifetime of 5 yr and 10 percent interest (capital recovery factor = 0.264), the gravel's annualized cost is \$5,000/mi-yr to \$9,200/mi-yr. For a 10-yr life, the cost reduces to \$3,100/mi-yr to \$5,700/mi-yr.

The use of a geotextile fabric or road carpet on unpaved roads reduces emissions by about 43 percent. The cost is estimated as about \$9,700/mi-yr (Levene and Drehmel, 1981).

In this section, costs for various control techniques are applied to the example TSDF's to generate a range of costs for each type. The types of sites considered are a 40-acre landfill, a dried lagoon (1 acre), a contaminated drum storage area (0.1 acre), an unpaved road (1 km), and a waste pile (1.8 acres). Each of these sites is described in greater detail in Section 8.

Several assumptions are required to derive the cost estimates. Examples are presented assuming the site is inactive, and other cases of a partially active site are presented for comparison. For example, the 40-acre landfill can be a facility no longer receiving waste or it could have a small portion in active use with the remainder of the site inactive.

Very few data are available for the expected lifetime of several of the control techniques. For covers of synthetic materials exposed to weathering, expected lifetimes of 5 to 10 years are used. A lifetime of 10 to 20 years is assumed for vegetative stabilization; however, longer lifetimes are possible if the vegetation is well established and thrives under the existing conditions of climate and nutrients. For chemical stabilization and wet suppression, costs are assumed to be incurred primarily as annual operating costs. Rented sprayers and receipt in drums are assumed for chemical stabilization instead of a capital investment in storage tanks (for bulk receipts) and in spray equipment.

Monitoring and maintenance costs are difficult to estimate because precise requirements cannot be identified for each source and control technique. The monitoring and maintenance cost of interest is the increase in cost to the operator for monitoring and maintaining the site after control is implemented. As discussed in Section 6, CFR Title 40, Parts 264 and 265 for TSDF's already require monitoring and maintenance by the operator, independent of application of a specific control technique for fugitive particulate emissions. For this reason, it is possible that the personnel used for monitoring and maintenance before a control is applied also could perform this function after a control technique is implemented. Implementing a control technique may actually decrease maintenance costs at a specific site. For example, vegetative covers or chemical stabilization may provide additional water erosion control with a corresponding savings in the cost of remedial actions to correct water erosion problems. Therefore, the monitoring and maintenance costs after control in this analysis are assumed to be about the same as the monitoring and maintenance costs before control. If specific information is available for additional monitoring and maintenance requirements at a particular site for a given control, these costs should be included in the annualized costs.

Results of these assumptions are that the costs of control techniques requiring frequent applications, such as chemical stabilization and wet suppression, are primarily annual operating costs. Controls such as covers, windscreens, and vegetative stabilization have significantly longer lifetimes and are treated as an installed capital cost. Annualized costs for these techniques are derived from annualizing the cost of capital over the assumed life of the control at an interest rate of 10 percent per year. Annualized capital cost is estimated by multiplying installed capital cost by the capital recovery factor that is determined by the life of the control and interest rate. Where a more appropriate lifetime or interest rate is available, annualized capital cost should be adjusted correspondingly.

Estimated control costs for a 40-acre landfill are given in Table 24. The first estimate for chemical stabilization assumes that part of the site is in active use and the balance is inactive. The cost is based on Bohn's study of controls for large active waste piles in Minnesota, which projected that 90+ percent control could be obtained from applications of approximately once per month during the wind erosion season. This cost was adjusted for 12 months instead of 3 months of control to account for year-round control. This cost may be biased high for two reasons: (1) less frequent applications may be required for the other 9 months, and (2) the percent of a landfill's total area that is active may be less than the percent of Bohn's wastepiles that were active. The second case assumes that the entire landfill area is inactive and that the absence of surface disturbances will result in less frequent applications of the stabilizer.

Costs for a synthetic film or foam cover are for the inactive portions of the site and are based on an assumed life of 5 to 10 years. These controls are not applicable for the active portion because operating equipment or waste placement would destroy their integrity. The option of covering with a soil layer also assumes a 5- to 10-year life; however, this life can be quite variable depending upon the extent of wind and water erosion. Soil covers may provide partial control at the active portion of the sites if a soil layer is added daily to cover the wastes. Also note that for liquid wastes, the soil cover may become contaminated and subject to wind dispersal after liquid absorption, adsorption, or capillary action.

The first case in Table 24 for vegetative stabilization assumes that adding a soil cover is already a part of routine operation or that the waste material supports vegetative growth without additional soil. The second case assumes that topsoil must be added to establish vegetation. This control is applicable only to inactive sites. The case for wet suppression first assumes that watering is used for only a small active portion and that some other technique is used for the balance of the site. The second case assumes the entire site must be watered periodically.

Estimated control costs for a dried lagoon are presented in Table 25. The site is inactive and can be controlled by one of several available techniques. A physical cover may be used to provide efficiencies approaching 100 percent. For long-term control and an efficiency less than 100 percent, vegetative stabilization, perhaps combined with chemical stabilization, may be an economical option if the site can support vegetation. Selection of wet suppression must be based on availability of water and potential to contaminate uncontaminated soil or water.

Table 26 contains cost estimates for control of fugitive emissions from soil surrounding a drum storage area. Costs for chemical stabilization depend upon site activity--increased activity increases the required frequency of application. Enclosing the area with a structure, such as a dome, is expensive and would likely need other benefits, such as reduced runoff or leachate generation, to justify the capital expenditure. If the site is abandoned, vegetative stabilization may be an economical long-term option.

Control cost estimates for unpaved roads are given in Table 27. Costs are variable, with costs highest for wet suppression and chemical stabilization. Efficiencies associated with these controls range from 30 percent for gravel to 90 percent for chemical stabilization.

Costs for chemical stabilization of an active waste pile in Table 28 are based on Bohn's estimates for active tailings piles in Minnesota. For covers, both active and inactive piles are considered. Active piles may require significant capital investment if the cover is installed with tension cables and an auger feed system for placing the wastes. Chemical stabilization and vegetative stabilization are relatively low-cost options with relatively high control efficiencies. Windscreens and wet suppression are also low-cost options; however, these options offer lower control efficiencies than those of chemical and vegetative stabilization.

TABLE 24. CONTROL COSTS FOR 40-ACRE LANDFILL

1. Chemical stabilization

   a. Assume most of the site is inactive and only a small portion is in active use. From Table 16, use \$888/acre/yr to \$2,720/acre-yr for 90+ percent control of active site (active waste pile from Bohn) from applications approximately once per month.

      Annualized cost = \$35,500 to \$109,000

   b. Assume the site is completely inactive and requires only annual applications of stabilizer. From Table 16, convert Bohn's estimate to a per-application basis (\$93/acre to \$230/acre).

      Annualized cost = \$3,700 to \$9,200

2. Cover

   a. Install a synthetic film cover at \$1/m^2 to \$6/m^2.

      Installed capital cost = \$162,000 to \$971,000
      Annualized cost (5-yr life) = \$43,000 to \$256,000
      Annualized cost (10-yr life) = \$26,000 to \$158,000

   b. Install a hardened foam cover, 2-in. thickness, at \$2.15/m^2 plus \$4,000 for equipment.

      Installed capital cost = \$352,000
      Annualized cost (5-yr life) = \$93,000
      Annualized cost (10-yr life) = \$57,000

   c. Cover with a 6-in. layer of locally available soil at \$1,500/acre.

      Installed capital cost = \$60,000
      Annualized cost (5-yr life) = \$16,000
      Annualized cost (10-yr life) = \$9,800

3. Vegetative stabilization (assumes site is inactive)

   a. Apply seed hydraulically with fertilizer and wood fiber mulch at \$1,800/acre (\$0.44/m^2).

      Capital cost = \$72,000
      Annualized cost (10-yr life) = \$12,000
      Annualized cost (20-yr life) = \$8,400

   b. Add 4 in. of topsoil at \$0.55/m^2 plus hydraulic seeding for a total of \$0.99/m^2.

      Capital cost = \$160,000
      Annualized cost (10-yr life) = \$26,000
      Annualized cost (20-yr life) = \$19,000

(continued)

TABLE 24 (continued)

4. Wet suppression--from the text of Section 6.2, watering costs range from $365/acre/yr to $1,270/acre-yr.

    a. Assume that only 1 acre of the site is active and that watering will be used only on the active portion.

        Annual cost = $365 to $1,270

    b. Assume that the entire 40 acres will be watered periodically to control emissions.

        Annual cost = $15,000 to $51,000

TABLE 25. CONTROL COSTS FOR A DRIED LAGOON (1 ACRE)

1. Chemical stabilization

   Assume the site is inactive and requires only one application per year.

Material cost ($0.13/m^2)	$526
Labor (8 h @ $23/h)	184
Equipment rental (1 day)	34
Annual cost	$744

2. Cover

   a. Install a synthetic film cover at $1/m^2 to $6/m^2.

   Capital cost = $4,000 to $24,000
   Annualized cost (5-yr life) = $1,000 to $6,300
   Annualized cost (10-yr life) = $650 to $3,900

   b. Install a hardened foam cover, 2 in. thick, at $2.15/m^2 plus $4,000 for equipment.

   Capital cost = $12,700
   Annualized cost (5-yr life) = $3,400
   Annualized cost (10-yr life) = $2,100

   c. Install a 6-in. layer of local soil over the site at $1,500/acre.

   Capital cost = $1,500
   Annualized cost (5-yr life) = $400
   Annualized cost (10-yr life) = $240

3. Vegetative stabilization

   a. Fine grade the site, seed, fertilize, and lime at $1.67/m^2.

   Capital cost = $6,800
   Annualized cost (10-yr life) = $1,100
   Annualized cost (20-yr life) = $800

   b. Apply seed hydraulically with fertilizer and wood fiber mulch at $0.44/m^2.

   Capital cost = $1,800
   Annualized cost (10-yr life) = $290
   Annualized cost (20-yr life) = $210

   c. Add 4 in. of local topsoil at $0.55/m^2 plus hydraulic seeding for a total of $0.99/m^2.

   Capital cost = $4,000
   Annualized cost (10-yr life) = $650
   Annualized cost (20-yr life) = $470

(continued)

TABLE 25 (continued)

4. Wet suppression

   a. Use locally available water with a total operating cost of $365/acre/yr to $1,270/acre-yr.

      Annual cost = $365 to $1,270

   b. Install a sprinkler system at $2.10/m^2 plus a sprinkler pump at $600.

      Capital cost = $9,100
      Annualized cost (10-yr life) = $1,500

TABLE 26. CONTROLS FOR DRUM STORAGE AREA
(190 m^2 contaminated)

1. Chemical stabilization

Material (at $\$0.13/\text{m}^2$)	$25
Labor (4 h at $23/h)	92
Equipment rental	34

Total cost for annual applications = $151
Total cost for monthly applications = $1,800

2. Cover

   a. Install a synthetic film cover at $\$1/\text{m}^2$ to $\$6/\text{m}^2$.

      Capital cost = $190 to $1,100
      Annualized capital cost (5-yr life) = $50 to $290
      Annualized capital cost (10-yr life) = $31 to $180

   b. Install a dome cover.

      Capital cost (Vogel and O'Sullivan, 1983) = $95,000 to $99,000
      Annualized capital cost (10-yr life) = $15,000 to $16,000
      Annualized capital cost (20-yr life) = $11,000 to $12,000

3. Vegetative stabilization (assumes site is inactive or abandoned)

   a. Fine grade, seed, and fertilize at $\$1.67/\text{m}^2$.

      Capital cost = $320
      Annualized cost (10-yr life) = $52
      Annualized cost (20-yr life) = $37

   b. Above plus 4 in. of local topsoil at $\$0.55/\text{m}^2$.

      Capital cost = $420
      Annualized cost (10-yr life) = $68
      Annualized cost (20-yr life) = $49

TABLE 27. CONTROL COSTS FOR AN UNPAVED ROAD
(0.5 mile)

1. Chemical stabilization--from Table 23, add Coherex® solution at a cost of $43,000/mi-yr to $65,000/mi-yr for 90+ percent control

   Annual cost = $22,000 to $33,000

2. Cover

   a. Add 3 to 6 in. of gravel at a cost of $19,000/mi to $35,000/mi

      Capital cost = $9,500 to $18,000
      Annualized cost (5-yr life) = $5,000 to $9,200

   b. Prepare and roll the sub-base, fine grade the area to be paved, and add 3 in. of bituminous paving at $107,000/mi

      Capital cost = $53,500
      Annualized cost (10- to 20-yr life) = $6,500 to $8,500

   c. Install road carpet for about 45 percent control. From Table 23, annualized cost is about $9,700/mi

      Annualized cost = $4,900

3. Wet suppression--water the road on dry days at a cost of $41,000/mi-yr to $63,000/mi-yr

   Annualized cost = $20,500 to $31,500

TABLE 28. CONTROL COSTS FOR A WASTE PILE
(1.8 acres)

1. Chemical stabilization--from Table 16, the cost is \$888/acre-yr to \$2,720/acre-yr for 90+ percent control on an active waste pile

   Annual cost = \$1,600 to \$4,900

2. Cover

   a. Assume the waste pile is inactive. Cover with a synthetic film material at \$1/m^2 to \$6/m^2.

      Capital cost = \$7,400 to \$45,000
      Annualized cost (5-yr life) = \$2,000 to \$12,000
      Annualized cost (10-yr life) = \$1,200 to \$7,300

   b. Assume the waste pile is in continuous, active use. Cover with synthetic film, use tension cables, and install an auger feed system. From Table 17, use \$43 to \$65/m^2.

      Capital cost = \$319,000 to \$483,000
      Annualized cost (5-yr life) = \$84,000 to \$128,000
      Annualized cost (10-yr life) = \$52,000 to \$79,000

   c. Install a hardened foam cover, 2 in. thick, at \$2.15/m^2 plus \$4,000 for equipment.

      Capital cost = \$20,000
      Annualized cost (5-yr life) = \$5,300
      Annualized cost (10-yr life) = \$3,300

3. Vegetative stabilization--assume the site is inactive

   a. Fine grade the surface, add seed, fertilizer, and lime at \$1.67/m^2.

      Capital cost = \$12,400
      Annualized cost (10-yr life) = \$2,000
      Annualized cost (20-yr life) = \$1,500

   b. Assume the waste pile will support vegetation. Use hydraulic application of seed, fertilizer, and wood fiber mulch at \$0.44/m^2.

      Capital cost = \$3,300
      Annualized cost (10-yr life) = \$540
      Annualized cost (20-yr life) = \$390

(continued)

TABLE 28 (continued)

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c. Add 4 in. of local topsoil at \$0.55/m^2 plus hydraulic seeding for a total of \$0.99/m^2.

    Capital cost = \$7,400
    Annualized cost (10-yr life) = \$1,200
    Annualized cost (20-yr life) = \$870

4. Windscreen--install a 2-m-high screen around the 290-m circumference at \$11 to \$42.70 per linear meter (installed)

    Capital cost = \$3,200 to \$12,400
    Annualized cost (10-yr life) = \$520 to \$2,000

5. Wet Suppression

    a. Water is readily available. Use \$365/acre-yr to \$1,270/acre-yr.

        Annual cost = \$660 to \$2,300

    b. Install a sprinkler system at \$2.10/m^2 plus a sprinkler pump at \$600.

        Capital cost = \$16,200
        Annualized cost (10-yr life) = \$2,600

A summary of costs and control efficiencies for the various sites is given in Table 1. Because of the lack of data on reductions in inhalable particles, the IP efficiency is evaluated with respect to total particle control. The far right column in Table 1 states whether control of inhalable particles is expected to be higher, lower, or the same as total particle control.

SECTION 8
EMISSION ESTIMATES AT EXAMPLE SITES

8.1 PREDICTION METHOD

A methodology can be formulated to predict downwind concentration of hazardous wastes emitted in fugitive particulate matter. Steps required are shown in Table 29 and discussed individually below.

For a given hazardous waste site, knowledge of its geographical location is a basis for finding generalized soil conditions and meteorological information. These items are required to determine degree of contamination (DOC) and to use dispersion equations for calculating downwind contaminant concentration.

Sites generally fall into one of four fugitive emission categories: line sources, area sources, storage piles, and point sources. The first three categories are useful for the hazardous waste sites considered in this report. Contaminated, unpaved roads can be represented by line sources; landfills, dried lagoons, and drum storage areas by area sources; and waste heaps by storage piles.

Knowledge of the type of contamination is required to judge potential toxic effects and to obtain chemical or physical properties for further estimation procedures. In particular, for organic chemicals, information in Section 4.3 is required to estimate adsorption coefficients.

The amount of erosion and subsequent air suspension of soil depends on its characteristics and on local climate. An adaptation of the wind erosion equation (WEE), discussed in Section 5.1, can be used to estimate soil loss to wind forces.

For soil loss to traffic and other mechanical activity, emission factor equations from Section 5.1 can be used.

The soil's organic carbon content must be measured or estimated to calculate the corresponding adsorption coefficient. If no other information is available, values of organic carbon content can be found from information in Section 4.3.

Tables 30 and 31 describe various types of hazardous waste sites and information required as part of the present methodology. Although each source is based on existing sites, some of the information has been generalized. For example, the haul road site is taken as a section of about 200 miles of North Carolina roadway along which used transformer oil was dumped

TABLE 29. METHODOLOGY FOR PREDICTING DOWNWIND CONCENTRATION OF HAZARDOUS FUGITIVE PARTICULATE

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1. Determine location (geographical coordinates)

2. Determine type of site:

   line source
   flat area
   storage pile

3. Determine type of contamination (chemical characteristics):

   specific chemicals and metals
   water solubilities
   octanol-water partition coefficient
   bioconcentration factor for aquatic life
   parachor

4. Determine soil and climate characteristics:

   parameters for wind erosion equation
   parameters for emission factor equations
   organic carbon content

5. Determine Degree of Contamination (DOC):

   use measured values (e.g., ppm of chemical in soil) or estimate from adsorption coefficient, K_{OC}; use degradation calculation if site age and rate constant or half-life are known

6. Calculate emission rate (controlled and/or uncontrolled) from:

   adaptations of wind erosion equations
   emission factor equations
   measured control efficiencies for similar sources and control techniques

7. Calculate amount of hazardous material in emitted dust from:

   DOC and emission rate

8. Determine meteorological conditions for location:

   parameters for industrial source complex (ISC) models

9. Apply ISC to calculate downwind concentration of hazardous material

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TABLE 30. EXAMPLE EMISSION SOURCES

Source and description	Major metal or organic material emitted	DOC	Uncontrolled emission rate	Emission model	Approximate location
1. Landfill--40-acre flat disposal area covered with contaminated soil.	Toluene	3,640 ppm (est.)	TSP 1.07 g/s IP 0.8 g/s	Area	Dearborn, MI
2. Dried lagoon--1-acre disposal pond in arid area with high evaporation rates.	Dieldrin	55.7 ppm (est.)	TSP 0.036 g/s IP 0.022 g/s	Area	Mecca, CA
3. Drum storage--10-ft soil strip surrounding concrete pad 125 ft in diameter.	dioxin (TCDD)	120 ppb (meas.) 4,144 ppm 0/078 ppm (est. with decay)	TSP 0.112 mg/s IP 0.067 mg/s (est.)	Area	Crestview, FL
4. Haul road--1-km section of dirt road in open countryside.	PCB (Aroclor 1260)	125 ppm (meas.) 141 pm (est.)	TSP 445 mg/s IP 223 mg/s	Line	Smithfield, NC
5. Waste pile--75 ft high with 950-ft circumference at base.	Pb and Zn	Pb 14,000 ppm (meas.) Zn 34,000 ppm (meas.)	TSP 1.16 g/s IP 0.87 g/s	Storage pile	Minera, Wales, U.K.

DOC = Degree of Contamination
TSP = Total Suspended Particulate
IP = Inhaleable Particulate

TABLE 31. EXAMPLE EMISSION SOURCES: SOIL CHARACTERISTICS

Source	Estimated particle size			
	Sand, % (0.05-2 mm)	Silt, % (0.002-0.05 mm)	Clay, % (<0.002 mm)	Organic carbon, %
1. Landfill	25	35	30	3
2. Dried lagoon	50	40	10	0.1
3. Drum storage	90	7	3	1
4. Haul road	45	35	20	7
5. Waste pile	Less than 22 mm			--

illegally. Measurements of several roadside soil samples indicated an average of about 125 ppm of PCB contamination, but the soil emission rate was generalized from numbers arbitrarily selected for use in an emission factor equation. The dried lagoon site exists, but pesticides are not a major waste constituent. The sites were chosen early in the project and treated as problem areas for which control and emission information were needed. The information was developed based on whatever sources were found and on assumptions necessary to provide reasonable answers.

Because of the few measured values found in the literature for DOC at hazardous waste sites, a means for estimating such values was sought. As mentioned in Section 4.3, the adsorption coefficient, K_{oc}, allows estimation of the amount of a given chemical adsorbed per unit weight of organic carbon in a specific soil. One disadvantage of using K_{oc} is its present limitation to pure compounds rather than mixtures. However, a series of estimates can be made based on chemicals of greatest interest in a particular hazardous waste site.

Once the climatological and mechanical activity rates have been established, calculating uncontrolled emission rates from emission factor equations should be relatively easy. Controlled emission rates can be taken as percentages of uncontrolled rates based on control method efficiency for total and inhalable particulate matter.

With known emission rates in terms of mass per unit time and DOC in terms of mass of contaminant per mass of soil, mass of hazardous material per unit time emitted to the air can be calculated. Calculation will be easiest for long-term averages and more difficult for shorter periods with fluctuating conditions.

When dispersion models such as the ISC model are to be used, meteorological conditions for the site location must be obtained. Either generalized values of windspeed and direction and stability can be used from published sources, or specific values can be obtained from recorded weather data near the site or from a nearby U.S. weather station. The information must conform to ISC model requirements as given in its user's guide.

The final step in the methodology is to calculate downwind dispersion based on the short- and/or long-term ISC models or other appropriate models. All information that is needed by either model will have been generated in previous steps but may require changes in form. Model outputs will be in micrograms per cubic meter of particulate matter at specific downwind locations. Concentration isopleths around the source also can be drawn. These concentrations of particulate matter can be converted to micrograms per cubic meter of hazardous material based on DOC found in step 5.

Models other than the ISC may be used for particular terrain configurations. For example, a valley model may be appropriate for sites located in a valley.

TABLE 32. EMISSIONS FROM EXAMPLE SITES

Source	Contaminant	DOC, µg/g	Uncontrolled emission rate				Controlled emission rate			
			TSP		Inhalable particulate		TSP		Inhalable particulate	
			Dust	Contaminant	Dust	Contaminant	Dust	Contaminant	Dust	Contaminant
1. Landfill	Toluene	3,640 (estimated)	1.07 g/s	3.9 mg/s	0.8 g/s	2.9 mg/s	0.16 g/s	0.59 mg/s	0.12 g/s	0.44 mg/s
2. Dried lagoon	Dieldrin	55.7 (estimated)	0.036 g/s	2.0 µg/s	0.022 g/s	1.23 µg/s	5.4 mg/s	0.30 µg/s	3.3 mg/s	0.185 µg/s
3. Drum storage	Dioxin (TCDD)	0.120 (measured) 0.078 (estimated, with decay)	0.112 mg/s	13.4 pg/s	0.067 mg/s	8.06 pg/s	16.8 µg/s	2.01 pg/s	10.1 µg/s	1.21 pg/s
4. Haul road	PCB (Aroclor 1260)	125 (measured) 141 (estimated)	1,790 mg/s	224 µg/s	897 mg/s	119 µg/s	269 g/s	33.6 µg/s	135 mg/s	17.9 µg/s
5. Waste pile	Pb and Zn	Pb 14,000 (measured)		16.2 mg/s		12.2 mg/s		2.43 mg/s		1.83 mg/s
		Zn 34,000 (measured		39.4 mg/s		29.6 mg/s		5.91 mg/s		4.44 mg/s
		combined)	1.16 g/s		0.87 g/s		0.174 g/s		0.131 g/s	

DOC = Degree of Contamination
TSP = Total Suspended Particulate

TABLE 33. CONTROLS FOR EXAMPLE SITES

Site	Control method	Efficiency		Control costs		Method chosen[a]
		Total	Inhalable	Capital	Annualized ($/yr)	
1. Landfill	Chemical stabilization	75-100	75-100	--	$3,700-$9,200	
	Vegetative plus chemical stabilization	85-100	85-100	72,000	$15,700-$21,200	√
2. Dried lagoon	Chemical stabilization	75-100	75-100	--	$744	
	Synthetic film cover	85-100	85-100	4,000-24,000	$1,000-$6,300	√
	Vegetative plus chemical stabilization	85-100	85-100	1,800-4,000	$1,030-$1,400	
3. Drum storage	Chemical stabilization	75-100	75-100	--	151-1,800	
	Synthetic film cover	85-100	85-100	190-1,100	50-290	√
4. Haul road	Chemical stabilization	40-96	40-96	--	22,000-33,000	
	Wet suppression	50	50	--	20,500-31,500	
	Paving	85	85	54,000	6,500-8,500	√
5. Waste pile	Chemical stabilization	75-100	75-100	--	1,600-4,900	
	Synthetic film cover	85-100	85-100	7,400-45,000	2,000-12,000	√
	Vegetative stabilization	50-80	50-80	3,300-7,400	540-2,000	
	Windscreen	30-80	30-80	3,200-12,400	3,200-12,400	

[a] The lowest efficiency for each chosen method was used to calculate controlled emission rates shown in Table 32.

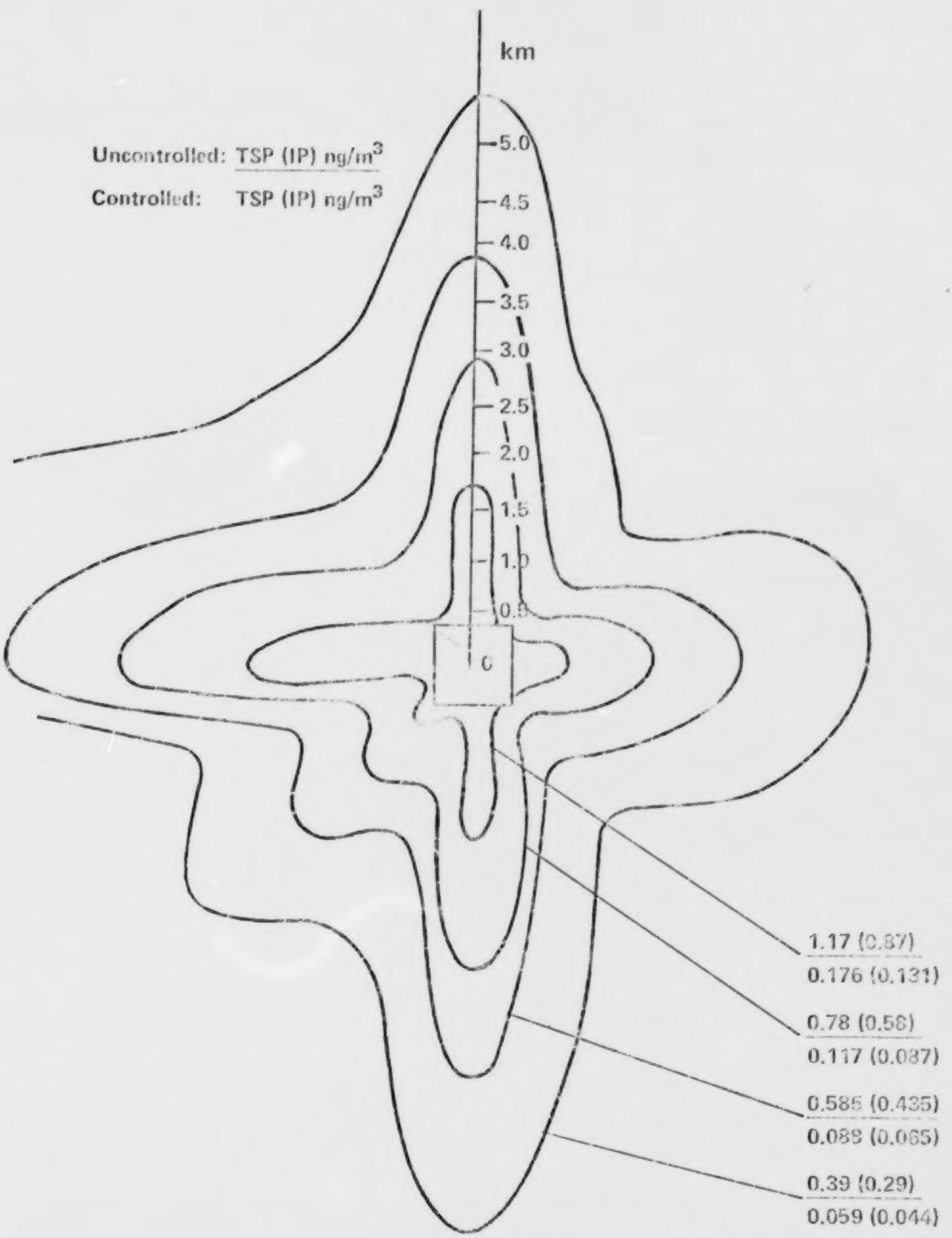
N
km
Uncontrolled: TSP (IP) ng/m3
Controlled: TSP (IP) ng/m3
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
1.17 (0.87)
0.176 (0.131)
0.78 (0.58)
0.117 (0.087)
0.585 (0.435)
0.088 (0.065)
0.39 (0.29)
0.059 (0.044)

Figure 6. Average annual contaminant concentration isopleths for Site 1, Landfill.

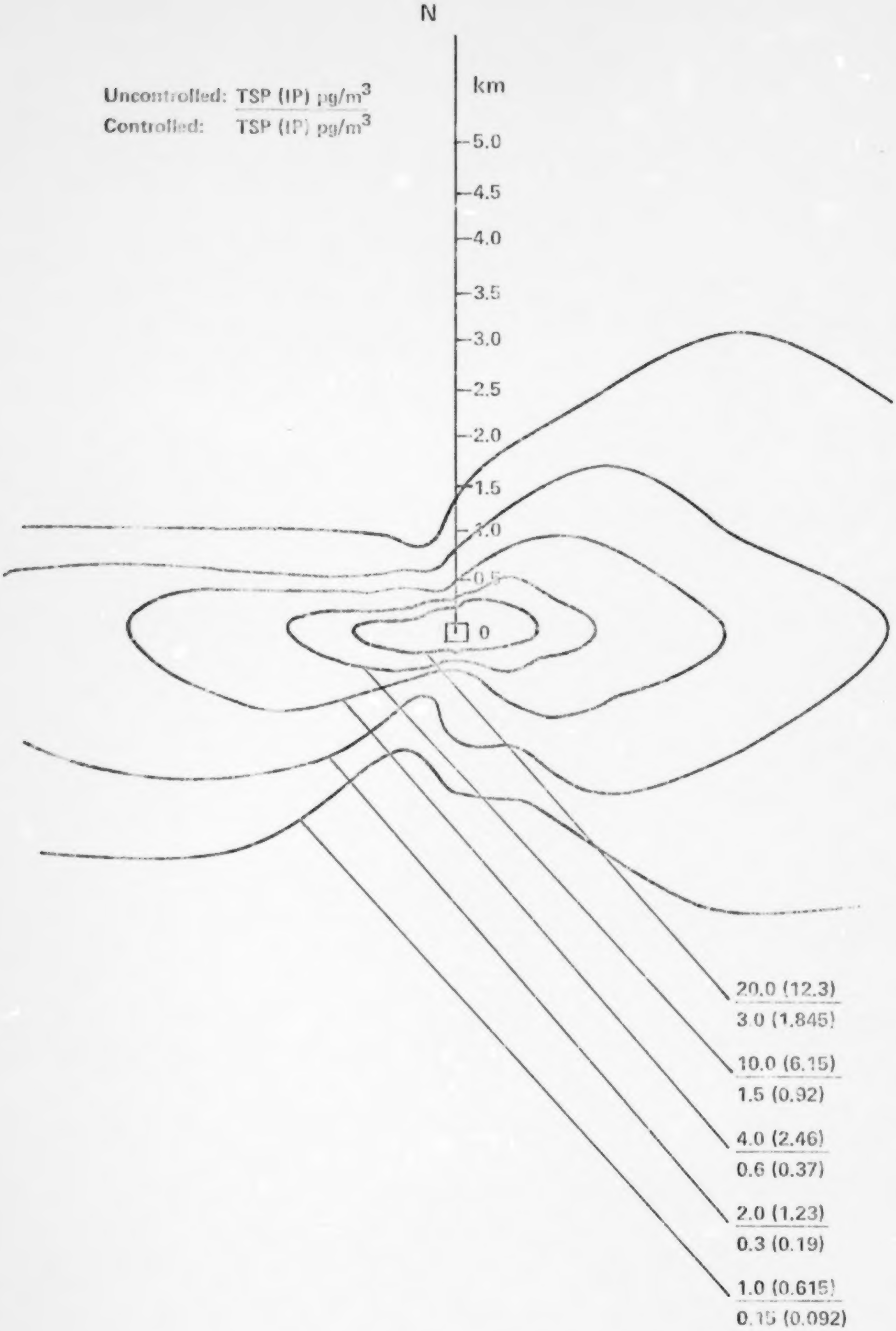

Figure 7. Average annual contaminant concentration isopleths for Site 2, Dried Lagoon.

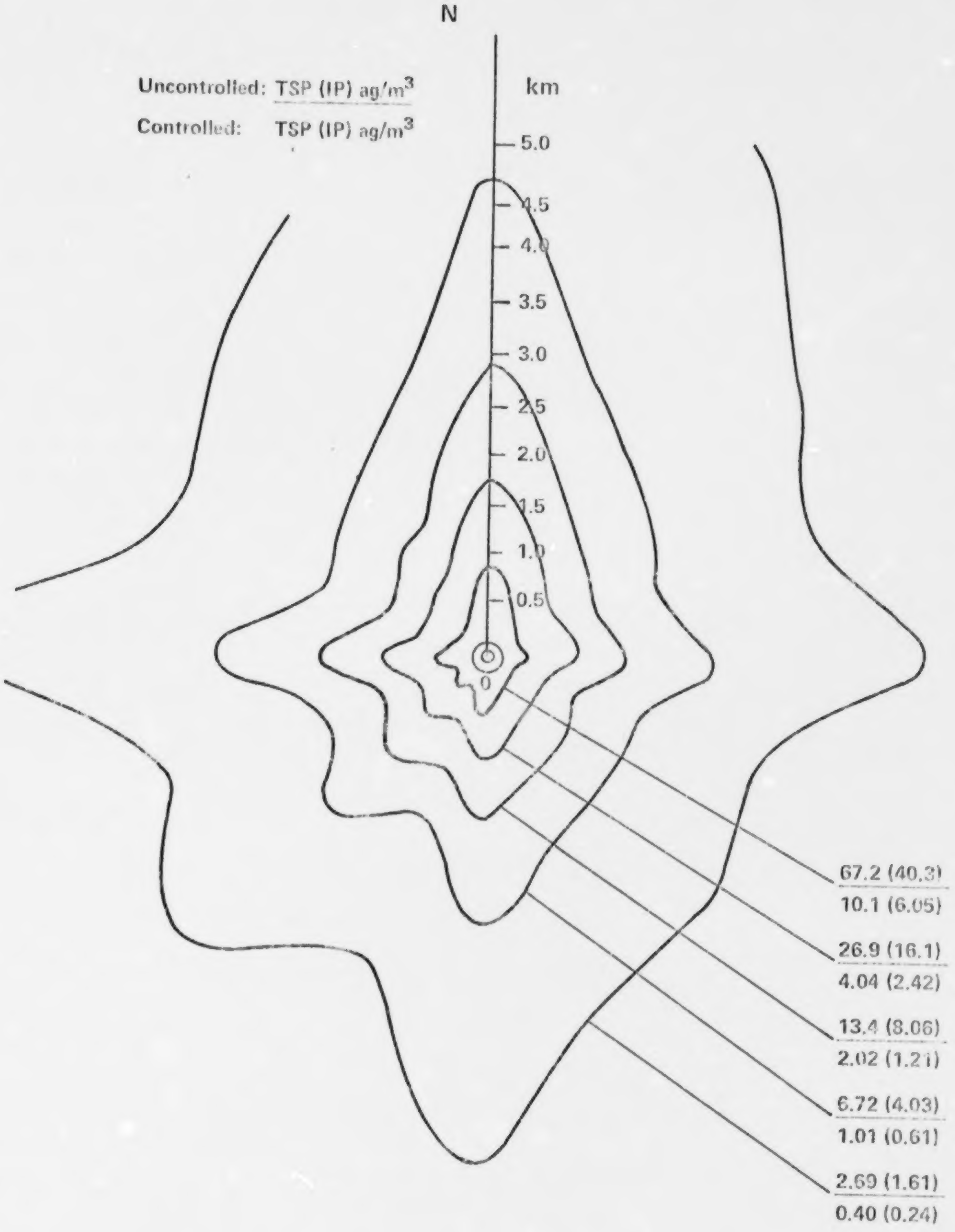

Figure 8. Average annual contaminant concentration isopleths for Site 3, Drum Storage.

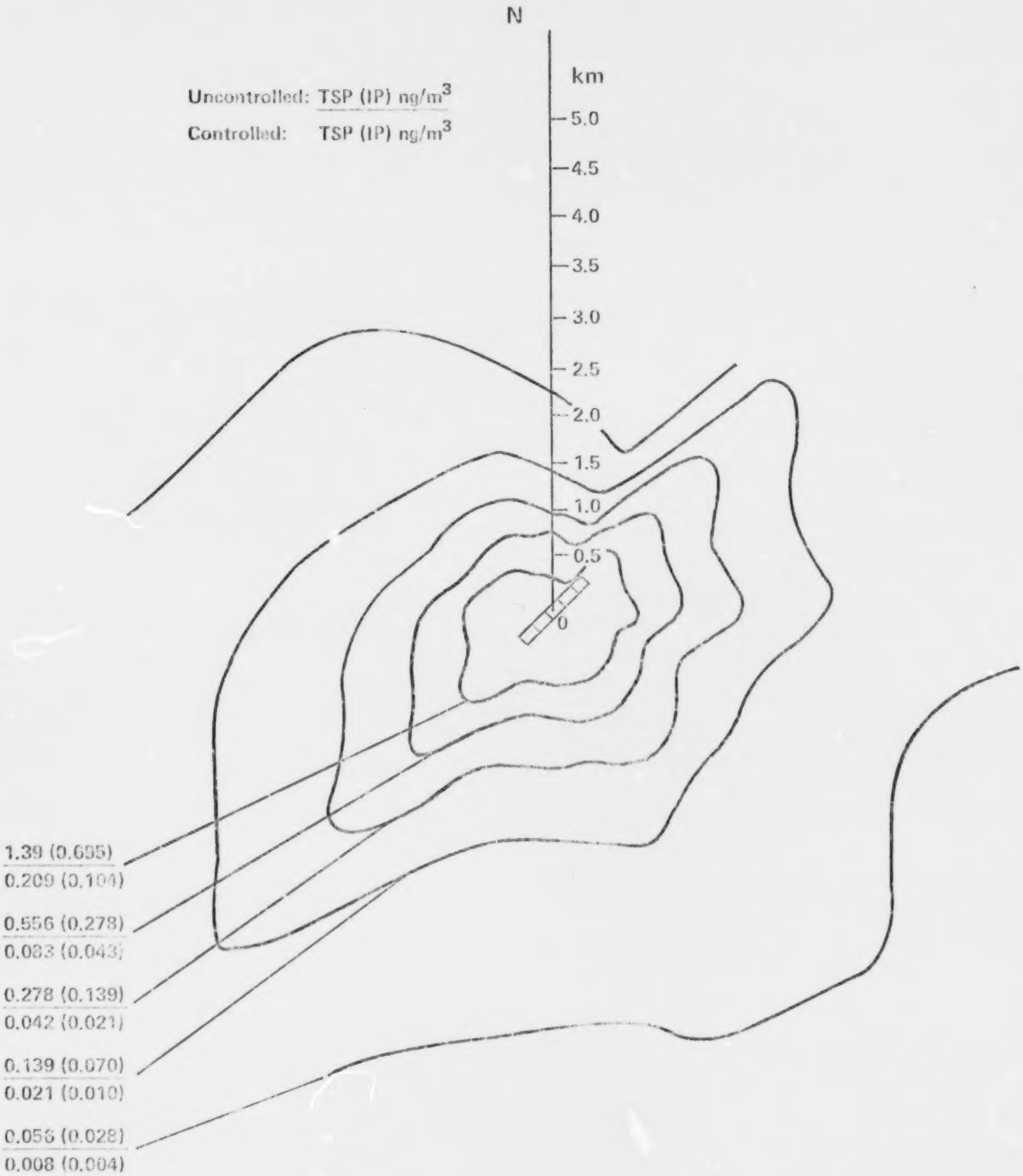
N
km
Uncontrolled: TSP (IP) ng/m3
Controlled: TSP (IP) ng/m3
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
1.39 (0.695)
0.209 (0.104)
0.556 (0.278)
0.083 (0.043)
0.278 (0.139)
0.042 (0.021)
0.139 (0.070)
0.021 (0.010)
0.056 (0.028)
0.008 (0.004)

Figure 9. Average annual contaminant concentration isopleths for Site 4, Haul Road.

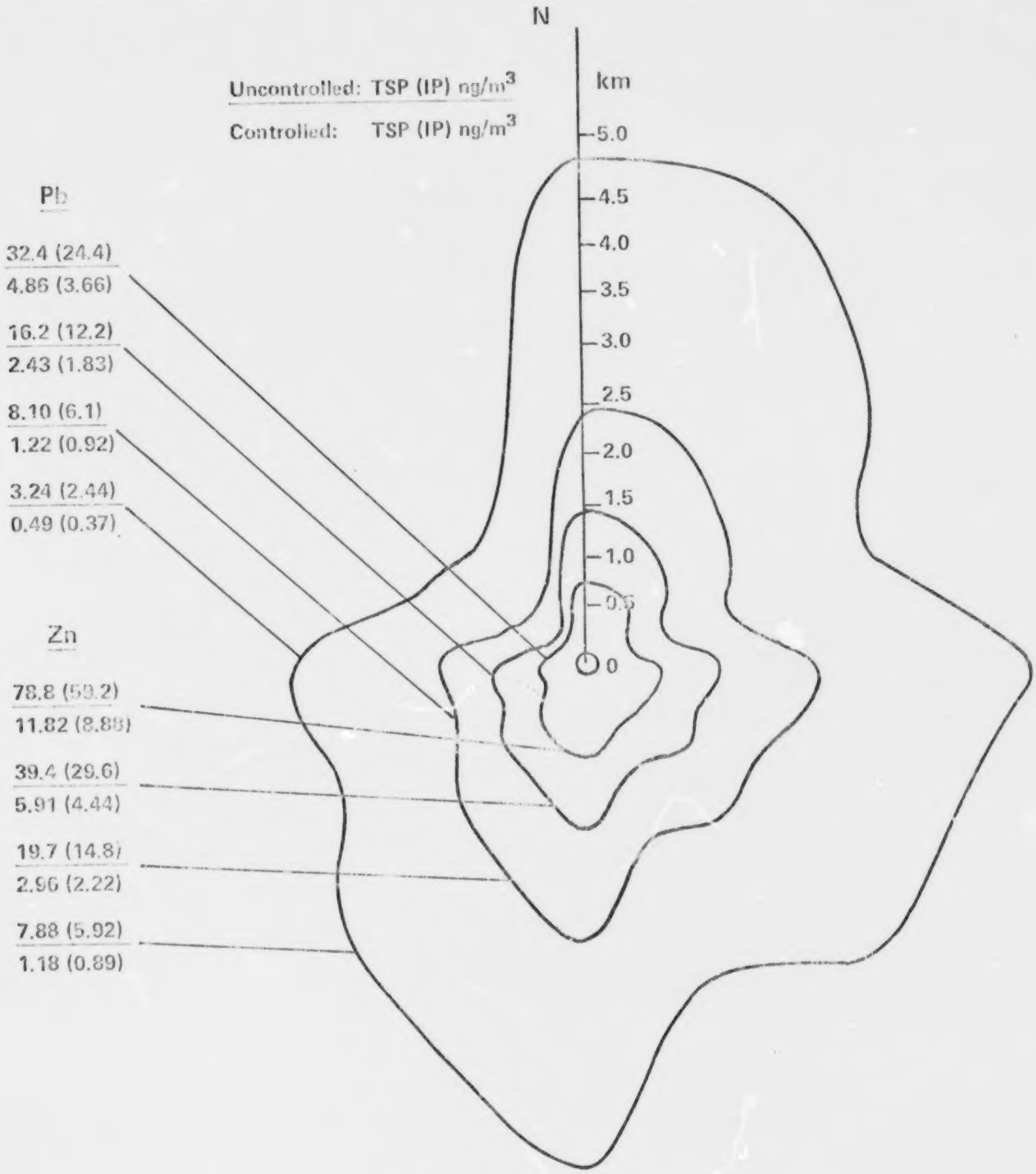
N
km
Uncontrolled: TSP (IP) ng/m3
Controlled: TSP (IP) ng/m3
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Pb
32.4 (24.4)
4.86 (3.66)
16.2 (12.2)
2.43 (1.83)
8.10 (6.1)
1.22 (0.92)
3.24 (2.44)
0.49 (0.37)
Zn
78.8 (59.2)
11.82 (8.88)
39.4 (29.6)
5.91 (4.44)
19.7 (14.8)
2.96 (2.22)
7.88 (5.92)
1.18 (0.89)

Figure 10. Average annual contaminant concentration isopleths for Site 5, Waste Pile.

8.2 EMISSION ESTIMATES

Calculations have been made for the five emission sources listed in Table 30 to determine DOC, uncontrolled and controlled emissions, downwind concentration of hazardous material, and control costs. Results are given in Tables 32 and 33. Calculations are shown in Appendix B. Concentration isopleths are presented in Figures 6 through 10. They show expected average annual downwind contaminant concentration, uncontrolled and controlled, for total suspended particulate (TSP) and inhalable particulate. No data are available to check the validity of these projections.

Comparison of measured versus estimated values of DOC is possible for two sites. Table 32 shows a surprisingly close difference of about 11 percent for the haul road example. The drum storage area example, however, shows a 35-percent lower estimation than was measured when a 10-year decay time is included in the calculations.

SECTION 9
LIMITATIONS AND FUTURE NEEDS

Major limitations of this work apply to calculations of degree of contamination (DOC) and downwind concentration of contaminant. Both quantities have been estimated, but few experimental data have been found to confirm the methodologies. DOC estimates are limited by lack of knowledge about specific sites, soil characteristics that change rapidly with distance, and the host of decay processes that reduce DOC with time. Especially for compounds that reside near the soil surface, photolytic or photooxidative reactions may change contaminants to innocuous compounds. Validity of the two major assumptions about DOC (i.e., adsorption from a saturated solution accounts for all of the contaminant retention, and first-order decay accounts for all of the degradation) remains to be established.

Although methods for estimating dispersion from emitting sources are well established, uncertainties about the methods are increased by uncertainties associated with the particle emission process from the earth's surface and with deposition processes, both dry and wet, that tend to reduce downwind concentration.

Measurements from experimental or existing hazardous waste sites are required to reduce the effects of the above-mentioned limitations. Many articles in the literature describe adsorption processes, degradation processes, soil properties, emissions, dispersion, or particle size effects; but no data sets have been found that follow the complete process from original contamination through measurement of downwind contaminant concentration over an extended period. When such data sets have been obtained for several sites, more confidence can be gained regarding the estimation methodology described earlier in the report.

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APPENDIX A

EXAMPLE SITE EMISSION CALCULATIONS

APPENDIX A

EXAMPLE SITE EMISSION CALCULATIONS

CALCULATIONS FOR EMISSION RATE: for five different sites.

1. Site 1:

Closed landfill (capped) with 40-acre flat disposal area covered with contaminated soil.

Location: Dearborn, Michigan
(suburb of Detroit, Michigan)

$$\begin{aligned} \text{Area} = 40 \text{ acres} &= 40 \times 4{,}074 \text{ m}^2 \\ &= 1.63 \times 10^5 \text{ m}^2 \\ &= 403.7 \times 403.7 \text{ m}^2 \\ &\text{or } 455.6 \text{ m circular area} \end{aligned}$$

Approximate site soil size distribution

% sand (2,000-75 μm)	-	35%
% silt (75-2 μm)	-	35%
% clay (<2 μm)	-	30%
		100%

Approach Wind Erosion Equation:

As described in U.S. Department of Agriculture (USDA) Agricultural Handbook No. 346, Skidmore and Woodruff (1968).

(i) % Dry soil fraction >840 μm
assumed to be 10%
(This needs to be determined accurately by sieving of soil)

-- Soil erodibility, I = 134 tons/acre-year

$$E_1 = I = 134 \text{ tons/acre-year}$$

(ii) For a flat and smooth field soil ridge roughness, $K_r = 0$ and the soil ridge roughness factor, K', = 1.0

$$E_2 = IK' = 134 \text{ tons/acre-year}$$

(iii) The climatic factor C' for Dearborn = 7% (annual average)

$$E_3 = IK'C'$$
$$= 134 \times 0.07$$
$$= 9.4 \text{ tons/acre/year}$$

(iv) Width of source ~ 400 m. (Assumed N-S)
Annual average wind direction = 127°
(East = 0, South = 90) with a preponderance factor, Rm, = 1.6
(Data for Ypsilanti, Michigan)

Thus, deviation of wind direction with respect to N-S = 37°

-- Corrected field length factor k_{50}

$= 1.85$ for $R_m = 1.5$
and $= 2.15$ for $R_m = 2.1$

-- for $R_m = 1.6$ $K_{50} = 1.9$

-- Corrected field length

$$L' = 1.9 \times 400$$
$$= 760 \text{ m}$$
$$\sim 2{,}500 \text{ feet.}$$

Now $E_4 = I'K'C'f(L')$

= 9.3 tons/acre-year (from graph in handbook)

(v) Finally, assuming no vegetative cover over the landfill (V=0),
soil loss rate = $E_5 = E_4\ f(V)$

$= E_4$

$= 9.3$ tons/acre-year

$E = 9.3$ tons/acre-year.

This is total soil loss due to wind erosion. Due to the fineness of soil, about 10% of the above value may be considered to be total suspended particulate (<30 μm) as opposed to a usual value of 2.5 to 3%.

-- total suspended particulate (TSP) emission rate

= 0.93 ton/acre-year

Using 40-acre area, and 1 ton = 2,000 lb
= 907.2 kg

The emission rate of TSP (<30 μm)

$= 0.93 \times 40 \times 907.2 \times 10^3$ g/yr

$= 3.375 \times 10^7$ g/yr

= 1.07 g/s.

Gillette's (1972) work indicates that the size distribution of suspended aerosols resembles that of its parent soil in the suspendable size range (<30 μm).

Defining inhalable particulates (IP's) as those less than 10 μm, and based on the size distribution of the soil, the IP/TSP ratio may be taken approximately as 0.75. Observations by Axetell and Cowherd at a Western surface coal mining site indicated an IP/TSP ratio for windblown emissions to be 0.67. Windblown emissions from storage piles also generally have an IP/TSP ratio in the range of 50 to 80%, where IP is defined as <10 μm and TSP is defined as <30 μm.

Thus, 0.75 seems a reasonable ratio.

Therefore:

Emission rate of TSP = $\underline{1.07}$ g/s

Emission rate of IP = $\underline{0.8}$ g/s.

Estimated contamination of the soil is approximately 3,640 ppm of toluene. Thus, the emission rate of toluene in the TSP's

$$= 1.07 \times 3,640 \times 10^{-6}$$

$$= \underline{3.9} \text{ mg/s.}$$

and in the IP's

$$= 2.9 \text{ mg/s.}$$

Similar calculations may also be performed using the unlimited erosion potential equation given by Cowherd et al., in their May 1984 report. The procedure outlined in that report is as follows:

For such a fine site soil size distribution, the size distribution mode (50th percentile) may be taken as 10 μm.

The threshold friction velocity is ~10 cm/s, and a corrected friction velocity to take into account larger size fractions may be taken as 20 cm/s.

Roughness height for a plowed field is ~1.0 cm.

The corresponding ambient windspeed at 7 m from ground for onset of wind erosion is ~15 × 20 cm/s.

$$U_t \sim 3.0 \text{ m/s.}$$

The emission rate for IP's may be expressed as:

$$E_{10} = A \times (1-V) \times [U]^3 F(X),$$

where

E_{10} = emission rate of inhalable particulates in g/m^2-h

$A = \text{constant} = 10^{-13} \frac{\text{gm s}^2}{\text{cm}^5}$

$= 10^{-3} \frac{\text{gm s}^2}{\text{m}^5}$

V = fraction of vegetative cover

[U] = mean annual windspeed, and

F(X) is a function of $\frac{Ut}{[U]}$, where U_t is a threshold value of windspeed.

For the Dearborn, Michigan, area,

$[U] \sim 4.6$ m/s.

and $F(X) \sim 1.91$.

Also V = 0

$$-- \quad E_{10} = 10^{-3} \times 1.0 \times 4.6^3 \times 1.91$$

$$= 0.186 \text{ g/m}^2\text{-h}$$

For the 40-acre site

$E_{10} = 8.4$ g/s.

This value is about an order of magnitude higher than that calculated using the wind erosion equation.

The main reason for this difference is the incorporation of a climatic factor in the wind erosion equation of about 0.07. If the same factor is applied to the MRI approach, $E_{10} \sim 0.59$ g/s, which is now comparable to the WEE.

2. Site 2:

A 1-acre dried lagoon disposal pond in arid area with high evaporation rates.

Location - California Desert near San Bernardino

Area = 1 acre = 4,074 m^2

= 64 × 64 m^2

or = 72 m diameter circle.

Approximate site soil size distribution

% sand (2,000-75 μm)	-	50%
% silt (75-2 μm)	-	40%
% clay (<2 μm)	-	10%
		100%

Approach Wind Erosion Equation:

As the site is located in an area with a high evaporation rate and involves a dried pond, the surface of the pond may be assumed to be fully crusted throughout the year. The soil erodibility based on the dry soil size distribution may be divided by 6 to take into account the effect of crusting as recommended by Skidmore and Woodruff (1968).

(i) The percent dry soil fraction >840 μm is assumed to be 15% (this again needs to be determined accurately by soil sieving).

-- Soil erodibility = I = 117 tons/acre-year

To account for crusting:

$$\text{Soil erodibility} = I = \frac{117}{6}$$

$$= 19.5 \text{ tons/acre-year}$$

(ii) For a flat and smooth field the soil ridge roughness, k_r, = 0 and the soil ridge roughness factor, k', = 1.0

-- $E_2 = IK'$

$= 19.5$ tons/acre-year

(iii) The climatic factor, C' for the San Bernardino area (annual average) is not available in climatic factor plots but may be estimated by:

$$C' = 34.483 \frac{V^3}{(P-E)^2} \quad ,$$

where V is the annual mean wind speed, and P-E is the precipitation-evaporation index.

The P-E index for San Bernardino ~ 14
and V ~ 9 mph (Las Vegas, NV)

$$C' = 34.483 \times \frac{9^3}{14^2}$$

$$= 128.3\ \%$$

Thus,

$$E_3 = IK'C'$$

$$= 19.5 \times 1.283$$

$$= 25.0 \text{ tons/acre-year.}$$

(iv) Width of source = 64 m (Assuming N-S orientation).
Annual average wind direction = 85°
with a preponderance factor, $R_m = 1.4$

(for Victorville north of San Bernardino in the desert)

Thus, the deviation of wind direction with respect to N-S = 5°

-- The corrected field length factor,

K_{50} = 1.9 for $R_m = 1.0$
and = 1.4 for $R_m = 1.5$
For $R_m = 1.4$, $K_{50} = 1.5$.

-- The corrected field length,

$$L' = 64 \times 1.5$$

$$= 96 \text{ m}$$

$$L' = 315 \text{ ft.}$$

Although the corrected field length of the source area is only 315 feet, it may be located in a wider surrounding area of much longer unsheltered length in the desert. Therefore, for a conservative estimate, no reduction in the emission rate is assumed due to an effect of unsheltered length.

-- $E_4 = IK'C'f(L') = 25.0$ tons/acre-year.

(v) Finally for no vegetative cover (V=0), the total soil loss rate E may be given by:

$$E = 25 \text{ tons/acre-year.}$$

Due to a 50% silt or finer content of the soil, the suspendable fraction may be assumed to be 5% (slightly higher than the 3% usually assumed).

-- The TSP emission rate (<30 μm)

$$= 25 \times 0.05$$

$$= 1.25 \text{ tons/acre-year.}$$

For a 1-acre area source and 1 ton = 2,000 lb,

The emission rate of TSP <30 μm = $1.25 \times 1.0 \times 907.2 \times 10^3$

$= 1.134 \times 10^6$ g/yr

= 0.036 g/s

The fraction of inhalable particles in the total suspended particles may be assumed to be similar to that in the parent soil size distribution in the <30 μm range.

-- $\frac{\text{IP } (<10\ \mu m)}{\text{TSP } (<30\ \mu m)} \sim 0.6$.

The emission rate of IP's

$\sim 0.6 \times 0.036$

$\sim \underline{0.022}$ g/s.

Contamination of the soil is estimated to be 55.7 ppm of Dieldrin. Therefore, the emission rate of Dieldrin in the TSP = $0.036 \times 55.7 \times 10^{-6}$ g/s

= 2.0 μg/s,

and Dieldrin emission in the inhalable size fraction = 1.23 μg/s.

Similar calculations may be carried out using the MRI report approach. Since the soil surface is crusted in this case, the soil may be expected to have limited erosion potential. A frequency of soil surface disturbance is required to determine the emission rate from such a source. For the present site, such a frequency of disturbance may be expected to negligible and no significant emissions are expected.

3. Site 3:

Drum storage - A 10-ft soil strip surrounding a concrete pad 125 ft in diameter. This site was used for temporary storage of drums before being transported by aircraft from the concrete landing pad. During this time the soil strip became contaminated. The site is no longer in use and no drums are stored.

Location: Near Crestview, Florida.

Area $\sim \Pi \times 135 \times 10$ ft^2

$\sim 4{,}240$ ft^2

Source width ~ 145 ft

Approximate site soil size distribution

% sand (2,000-75 μm)	-	90%
% silt (75-2 μm)	-	7%
% clay (2 μm or less)	-	3%
		100%

Approach Wind Erosion Equation:

(i) The percent dry soil fraction > 840 μm is assumed to be 30% (1/3 of the total sand fraction) for a conservative estimate.

Soil erodibility = I = 74 tons/acre-year.

(ii) For a flat and smooth field, soil ridge roughness, K_r, = 0 and the soil ridge roughness factor = K' = 1.0

$$E_2 = IK' = 74 \text{ tons/acre-year}$$

(iii) The climatic factor, C', for the Crestview Area ~ 2%

~ 0.02

$$\begin{aligned} E_3 &= IK'C' \\ &= 74 \times 0.02 \\ &= 1.5 \text{ tons/acre-year.} \end{aligned}$$

(iv) The width of the source area is fairly small, but the source may be assumed to be located in a wide, unsheltered area for conservative estimates.

In this case:

$$\begin{aligned} E_4 &= IK'C'\ f(L') = E_3 \\ &= 1.5 \text{ tons/acre-year.} \end{aligned}$$

(v) For no vegetative cover over the source area (V=0), the total soil loss rate, E, = E_4

$$= 1.5 \text{ tons/acre-year.}$$

The emission rate of TSP's may further be assumed to be 2.5% of the soil loss rate.

-- The emission rate of TSP's (<30 μm) ~ 1.5 × 0.025 ~ 0.04 tons/acre-year

Based on soil size distribution, the fraction of IP's in the TSP's may be considered to be 0.6.

-- Rate of emission of IP's

$$= 0.024 \text{ ton/acre-year}$$

For a source area of 4,240 ft^2:

$$\text{Emission rate of TSP} = \frac{0.04 \times (907.2 \times 10^3)}{365 \times 24 \times 3{,}600} \times \frac{4{,}240}{43{,}560}$$

$$= 1.12 \times 10^{-4} \text{ g/s}$$

Emission rate of TSP = 0.112 mg/s

Emission rate of IP = 0.067 mg/s.

Contamination of the soil is ~ 120 ppb of Dioxin.

Therefore, the emission rate of dioxin in the TSP ~ $0.112 \times 120 \times 10^{-9}$ mg/s

$\sim 1.344 \times 10^{-5}$ µg/s

$\sim \underline{13.44}$ pg/s;

and the emission rate of Dioxin in the IP ~ $\underline{8.06}$ pg/s

Calculations were not carried out using the Cowherd et al. (1984) approach since the unlimited erosion potential equation does not take into account the climatic correction factor and the frequency of disturbance value required for the limited erosion potential equation is not available.

4. Site 4:

Haul road - A 1-km section of unpaved dirt road in open countryside.

Location - Central North Carolina (Goldsboro-Raleigh area)

To facilitate dispersion calculations, the 1-km section may be divided into five sections of 200 m each, which may be considered individual point sources in the atmospheric dispersion calculations.

A calculation developed by Cowherd et al. (1984) to estimate the emission rate of IP's (<10 µm) may be used for this purpose. This equation is a modified version of one given in AP-42. By comparing the two equations, the original in AP-42 predicts total emission rate; the TSP fraction (<30 µm) is approximately 60% of total emissions. Further, half of the TSP may be assumed to be inhalable (<10 µm) to arrive at the proposed equation by Cowherd et al. (1984).

The IP emission rate may be estimated by:

$$E_{10} = 0.85 \left(\frac{s}{10}\right) \left(\frac{S}{24}\right)^{0.8} \left(\frac{W}{7}\right)^{0.3} \left(\frac{w}{6}\right)^{1.2} \left(\frac{365-p}{365}\right) ,$$

where

E_{10} is the emission rate of IP's from an unpaved road per vehicle-kilometer of travel, kg/VKT

s is the silt content of the road surface material, % (i.e., particles smaller than 75 μm)

S is the mean vehicle speed, km/h

W is the mean vehicle weight, Mg

w is the mean number of wheels

p is the number of days with at least 0.01 in. of precipitation per year.

Approximate site soil size distribution:

% sand (2,000-75 μm)	45%
% silt (75-2 μm)	35%
% clay (<2 μm)	20%
	100%

Considering heavy vehicle traffic with $W = 10$ Mg, $w = 10$ wheels, $S = 80$ km/h, p for central North Carolina ~ 120, and $s = 35 + 20 = 55\%$,

$$E_{10} = 0.85 \left(\frac{55}{10}\right) \left(\frac{80}{24}\right)^{0.8} \left(\frac{10}{7}\right)^{0.3} \left(\frac{10}{6}\right)^{1.2} \frac{245}{365}$$

$$= 16.9 \text{ kg/VKT}$$

Considering traffic volume as 8 vehicles/day on all working days,

$$\text{VKT/year} = 8 \times 5 \times 52 \times \frac{200}{1{,}000}$$

$$= 416 \text{ km/yr}$$

over the 200-m section of the road.

-- The emission rate of IP's from a 200-m section of the road

$$= 416 \times 16.9$$

$$= 7{,}030.4 \text{ kg/yr}$$

$$= 0.223 \text{ g/s}$$

$$= 223 \text{ mg/s.}$$

The rate of TSP emissions may be considered as twice the IP. Measurements by Axetell and Cowherd (1981) on emissions from haul trucks on unpaved roads at a Western surface coal mining site indicated that IP/TSP = 0.52.

Thus, the emission rate of total suspendable particles = 446 mg/s.

Another correlation developed by Bohn et al. (1978) to estimate TSP emissions from unpaved roads in the iron and steel industry may be used for comparison.

Their equation is given as:

$$E = 5.9 \left(\frac{s}{12}\right) \left(\frac{S}{30}\right) \left(\frac{W}{3}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5} \left(\frac{365-p}{365}\right) ,$$

where

E = lb/VMT of TSP emissions (<30 μm)

S = vehicle speed in mph

W = vehicle weight in tons.

Using the data given before,

$$E = 5.9 \left(\frac{55}{12}\right) \left(\frac{50}{30}\right) \left(\frac{10 \times 2.2}{2 \times 3}\right)^{0.7} \left(\frac{10}{4}\right)^{0.5} \frac{245}{365}$$

$$= 118.8 \text{ lb/VMT}$$

$$= 33.7 \text{ kg/VKT.}$$

Therefore, the emission rate of TSP (<30 μm) predicted by this equation (from a 200-m section)

$$\sim 33.7 \times 416 \text{ kg/yr}$$

$$\sim 0.445 \text{ g/s}$$

$$\sim 445 \text{ mg/s}$$

This rate is identical to that calculated by the first equation.

The emission rate of TSP from the 200-m section of contaminated road = 445 mg/s.

The emission rate of IP from the 200-m section of contaminated road = 223 mg/s.

Contamination of the road soil is approximately 125 ppm of PCB (Aroclor 1260).

The emission rate of PCB in the TSP from a 200-m section of contaminated road

$$= 445 \text{ mg/s} \times 125 \times 10^{-6}$$

$$= 0.0556 \text{ mg/s}$$

$$= 55.6 \text{ µg/s}$$

The emission rate of PCB in the IP from a 200-m section of contaminated road

$$= 27.8 \text{ µg/s}$$

5. Site 5:

Waste pile - 75 ft high with a 950-ft circumference at the base.

Location: Minera, Wales

The actual location is approximated to one located near Seattle/Tacoma area in Washington. This location is chosen for its climatological similarity to the Wales region and availability of climatic data for this area.

Diameter of base ~ 302 ft

$$\text{Source area} = 7.182 \times 10^4 \text{ ft}^2$$
$$= 1.65 \text{ acres}$$

An approximate waste pile particle size distribution, may be taken as 45% silt (particles smaller than 75 µm).

The average emission rate from a waste pile due to wind erosion may be estimated by an equation recommended by Cowherd et al. (1984). The equation was originally developed from experiments on gravel and aggregate piles and also from storage in piles iron and steel industry.

The emission rate of total suspended particles (TSP, <30 µm) is given by:

$$E = 1.7 \left(\frac{s}{1.5}\right) \left(\frac{365-p}{235}\right) \left(\frac{f}{15}\right)$$

where

E is the emission rate of TSP in lb/day/acre due to wind erosion

s is the silt content of pile, %

p is the number of days per year with at least 0.01 in. of precipitation f is the percentage of time that the unobstructed windspeed exceeds 12 mph at the mean pile height.

For the Seattle/Tacoma area, p = 180 and the assumed silt content = 45%

The percent of time the windspeed exceeds 12 mph at surface level = 36% (at Seattle/Tacoma airport)

Since the pile height is 75 ft (25 m), the frequency of windspeed exceeding 12 mph will be higher at the mid-pile height than that given at the ground level (7 m above ground), which is 36%.

The percent of time that the windspeed exceeds 12 mph at the mean pile height may be taken on 50% (f = 50).

Thus, using the above equation:

$$E = 1.7 \left(\frac{45}{1.5}\right) \left(\frac{365-180}{235}\right) \left(\frac{50}{15}\right)$$

$$= 133.8 \text{ lb/acre-day}$$

TSP emissions from the waste pile (<30 μm)

$$= \frac{133.8 \times 454 \times 1.65}{24 \times 3,600} \text{ g/s}$$

$$= 1.16 \text{ g/s}$$

Wind erosion of storage piles generally produces a greater fines fraction than that found in the parent material. A typical size distribution given by PEDCO (1977) indicates an IP (<10 μm) to TSP (<30 μm) emissions ratio of 0.75 (IP/TSP = 0.75).

Therefore, using this value:

The emission rate of inhalable particulates from the waste pile ~ 0.87 g/s.

The contaminant concentrations in the pile material are approximately 14,000 ppm of lead and 34,000 ppm of Zn.

The emission rate of Pb in the TSP = $1.16 \times 14,000 \times 10^{-6}$ g/s
= $\underline{16.2}$ mg/s.

The emission rate of Pb in the IP = $\underline{12.2}$ mg/s.

The emission rate of Zn in the TSP = $\underline{39.4}$ mg/s.

The emission rate of Zn in the IP = $\underline{29.6}$ mg/s.

Uncontrolled emission rates for all five sites are presented in Table A-1.

Atmospheric Dispersion Calculations

Dispersion of fugitive particulate emissions in the atmosphere may be estimated by using atmospheric dispersion equations such as the gaussian diffusion equation, by ignoring particle inertia or settling and fallout of particles. A long-term average probability distribution of windspeed with respect to its magnitude, direction, and stability conditions is needed to obtain long-term average downwind concentrations due to an emission source. Such probability distributions called STAR tabulations are compiled by the National Climatic Center for various locations throughout the United States. These distributions are available for both seasonal and annual average distributions. For the present purpose, long-term (e.g., 1 to 5 years) annual average distribution is required. A typical distribution gives probability distribution values for six stability classes. For each stability class, values are given for 6 windspeed classes and 16 sectors (22.5° each). Thus, a complete STAR tabulation typically consists of $6 \times 6 \times 16 = 576$ f_{ijk} elements (i, stability class; j, windspeed class; and k, sector).

Given such a wind probability distribution, a dispersion equation describing downwind concentration at a distance x from a point source and in a sector k may be written as (Slade, 1968):

$$C(x, k) = 2.03\, Q \sum_{i=1}^{6} \frac{1}{(\sigma_z)_{i,x}\, x} \sum_{j=1}^{6} \frac{f_{ijk}}{u_j}, \qquad \text{(A1)}$$

where

$(\sigma_z)_{i,x}$ = is the vertical dispersion coefficient and is a function of stability class i, and downwind distance x.

Q = is the source emission rate expressed in mass rate per unit time (e.g. gm/sec)

u_j = is the mean windspeed for windspeed class j

f_{ijk} = is the probability of wind in stability class i, windspeed class j and direction in sector k.

Note that:

$$\sum_{i=1}^{6} \sum_{j=1}^{6} \sum_{k=1}^{16} f_{ijk} = 1.0$$

This equation is applicable for ground level source and receptor locations.

TABLE A-1. UNCONTROLLED EMISSION RATES

Site #	TSP	IP	Contaminant and its concentration	Concentration in TSP emission	Concentration in IP emission
1	1.07 g/s	0.8 g/s	3,640 ppm of toluene	3.9 mg/s	2.9 mg/s
2	0.036 g/s	0.022 g/s	55.7 ppm Dieldrin	2.0 μg/s	1.23 μg/s
3	0.112 mg/s	0.067 mg/s	120 ppb Dioxin	13.44 pg/s	8.06 pg/s
4 (200 m section of road)	445 mg/s	223 mg/s	125 ppm PCB (Aroclor 1260)	55.6 μg/s	27.8 μg/s
5	1.16 g/s	0.87 g/s	14,000 ppm Pb	16.2 mg/s	12.2 mg/s
			34,000 ppm Zn	39.4 mg/s	29.6 mg/s

The vertical diffusion coefficient $(\sigma_z)_{i,x}$ depends upon the stability class and downwind distance and may be expressed as:

$$(\sigma_z)_{x,i} = a\, x^b + d \quad , \tag{A2}$$

where a, b, and d are fitted coefficients and all are functions of stability class i and distance x. The values of a, b, and d are given in the Valley Model User's Guide (EPA, 1977c) and are used in the present calculations.

Equation (A1) is for a point source. A point source may be assumed upwind of the area source with the same emission rate as shown in Figure A1 in order to simulate an area source. The distance of the point source from the area source is such that it gives the same downwind concentration as is given by the area source.

The distance S, to predict the same downwind concentration, depends upon the source width W and the stability class and is expressed as (Dynamac, 1983):

$$S_i = C_i\, W \quad , \tag{A3}$$

where C_i is a constant depending upon the stability class i.

Equation (A1) is then modified as:

$$C(x,\, k) = 2.03\ EA \sum_{i=1}^{6} \frac{1}{(\sigma_z)_{i,x+S_i}\ (x+S_i)} \sum_{j=1}^{6} \frac{f_{ijk}}{u_j} \quad , \tag{A4}$$

where E is the emission rate per unit area and A is the source area (Q = EA).

Once STAR or frequency tabulations for a desired area are obtained, calculations for downwind concentration using Equation (A4) are straightforward.

For a line source, the source length may be broken into small segments such that each of the segments may be approximated as a point source. The dispersion calculations may be carried out for each point source. The downwind concentration at a given location is then obtained by summing the concentrations at that location generated by each point source.

A computer program was written in BASIC language to solve Equation (A4). The program determines downwind concentration, from a point or area source, for several downwind distances in each of 16 sectors. STAR tabulations provide a wind probability distribution for the source. The program listing is included here.

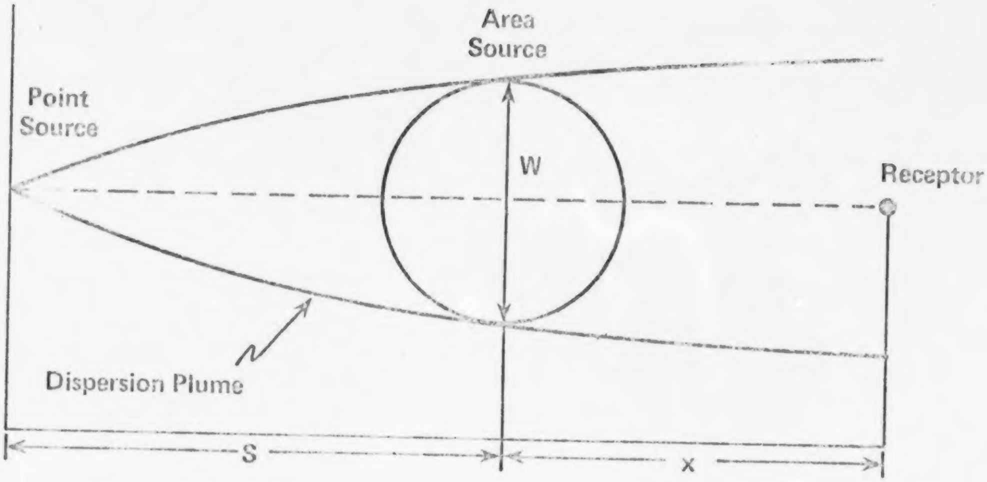
Area
Source
Point
Source
W
Receptor
Dispersion Plume
S
x

Figure A1. Simulation of area source from point source.

```
10 REM : PROGRAM TO CALCULATE DOWNWIND CONCENTRATIONS USING GUASSIAN DISPERSION
20 REM: INPUT FROM STAR TABLES
30 DIM P(6,6,16),U(6),M(20,16),A(6,2),B(6,2),D(6,2),S(6),C(6)
40 INPUT "FILE NAME FOR INPUTDATA",A$
50 OPEN "I",#3,A$
60 FOR I= 1 TO 6
70 FOR J=1 TO 6
80 FOR K =1 TO 16
90 INPUT #3,P(I,J,K)
100 T=T+1
110 NEXT K
120 NEXT J
130 NEXT I
140 CLOSE #3
150 FOR J=1 TO 6
160 PRINT "READ AVERAGE WIND SPEED FOR EACH CLASS--U(";J;")"
170 READ U(J)
180 LPRINT "AVERAGE WIND SPEED FOR CLASS";J;"=  ";U(J);"KNOTS/HR"
190 U(J)=U(J)*.5144
200 LPRINT "AVERAGE WIND SPEED FOR CLASS";J;"=  ";U(J);"METERS/S"
210 NEXT J
220 FOR I= 1 TO 6
230 PRINT "READ CONSTANT C("I";) FOR STABILITY CLASS";I
240 READ C(I)
250 NEXT I
260 REM:L=1 IF X>1000M. AND L=2 IF 100M.<=X<1000M.
270 LPRINT
280 LPRINT
290 LPRINT
300 LPRINT "                  VERTICAL DIFFUSION COEFFICIENT"
310 LPRINT "A(I,L)","B(I,L)","D(I,L)"
320 FOR L=1 TO 2
330 FOR I=1 TO 6
340 PRINT "INPUT CONSTANTS A(";I;L;"),B(";I;L;"); AND D(";I;L;")"
350 READ A(I,L),B(I,L),D(I,L)
360 LPRINT A(I,L),B(I,L),D(I,L)
370 NEXT I
380 NEXT L
390 PRINT "INPUT 1 IF AREA SOURCE AND 2 IF POINT SOURCE, AND W=WIDTH OF SOURCE"
400 LPRINT "INPUT 1 IF AREA SOURCE AND 2 IF POINT SOURCE, AND W=WIDTH OF SOURCE"
410 INPUT SOURCE,W
420 PRINT "SOURCE=  ";SOURCE,"SOURCE WIDTH=  ";W
430 LPRINT "SOURCE TYPE=  ";SOURCE,"SOURCE WIDTH=  ";W
440 LPRINT
450 LPRINT
460 LPRINT
470 LPRINT "        VOLUMETRIC CONCENTRATIONS"
480 LPRINT "SECTOR","DISTANCE ","UNIT CONCENTRATION"
485 INPUT "FILE NAME FOR OUTPUT",B$
490 OPEN "O",#2,B$
500 FOR K=1 TO 16
```

```
510 FOR X=.5 TO 5 STEP .5
520 SUM2=0
530 FOR I=1 TO 6
540 IF X=>1 THEN L=1 ELSE L=2
550 IF SOURCE=1 THEN 560 ELSE 580
560 S(I)=W*C(I)
570 GOTO 590
580 S(I)=0
590 SIGMAZ=A(I,L)*(1000*X+S(I))^B(I,L)+D(I,L)
600 SUM1=0
610 FOR J=1 TO 6
620 SUM1 =SUM1+P(I,J,K)/U(J)
630 NEXT J
640 SUM2=SUM2+SUM1*2.03/SIGMAZ/((X*1000)+S(I))
650 NEXT I
660 M(2*X,K)=SUM2
670 PRINT "M("X;K")=  ";M(2*X,K)
680 PRINT #2,SUM2
690 LPRINT K,X,M(2*X,K)
700 NEXT X
710 NEXT K
720 CLOSE #2
730 DATA 1.5,5.0,8.5,13.5,19.0,27.0
740 DATA 1.17,1.61,2.4,3.57,6.25,6.25
750 DATA .001,1.89,9.6,.0476,1.11,2.0,.119,.915,0
760 DATA 2.61,.45,-25.5,52.6,.15,-126.0,33.0,.14,-75.0
770 DATA .001,1.89,9.6,.0476,1.11,2.0,.119,.915,0
780 DATA .187,.755,-1.4,.1345,.745,-1.1,.362,.55,-2.7
800 END
```

CALCULATIONS FOR DEGREE OF CONTAMINATION

Site 1, landfill

Solubility of toluene = 0.05 g/100 g water = 500 ppm = 500 μg/mL (Perry's Chemical Engineers' Handbook, Fourth Edition. Edited by Perry, Chilton, Kirkpatrick. McGraw-Hill, 1950).

K_{oc} for toluene using Equation (29), Table 3.

$$\begin{aligned} \text{Log } K_{oc} &= -0.55\ (\log 500) + 3.64 \\ &= 2.16 \\ K_{oc} &= 143.08 \end{aligned}$$

K_{oc} for toluene using Equation (30), Table 3.

$$\begin{aligned} \text{Log } K_{oc} &= -0.54\ (\log 9.77 \times 10^{-5}) + 0.44 \\ &= 2.61 \\ K_{oc} &= 403.14 \end{aligned}$$

Averaging the logs of the two equations:

$$\frac{2.16 + 2.61}{2} = 2.39 = \log K_{oc}$$

$$K_{oc} = 242.66$$

DOC, using organic carbon content from Table 6:

$$\begin{aligned} d &= K_{oc} C_o S \\ &= (242.66)(0.03)(500) \\ &= 3{,}640\ \mu g/g \end{aligned}$$

Site 2, Dried Lagoon

Solubility of dieldrin = 186 μg/L (from Resource Conservation Recovery Act [RCRA] listing document)

$$\text{Log } K_{ow} = 6.2 \text{ (Briggs, 1981)}$$

$$\begin{aligned} \text{Log } K_{oc} &= 0.544 \log K_{ow} + 1.377 \text{ (Equation 32, Table 3)} \\ &= 4.750 \\ K_{oc} &= 56{,}208 \\ \text{Log } K_{oc} &= 1.029 \log K_{ow} - 0.18 \text{ (Equation 36, Table 3)} \\ &= 6.200 \\ K_{oc} &= 1.584 \times 10^{6} \end{aligned}$$

Averaging logs:

$$\frac{4.750 + 6.00}{2} = 5.475$$

$$K_{oc} = 29{,}900$$

DOC, using organic carbon content from Table 5:

$$d = (29{,}900)(0.001)(0.186)$$
$$= 55.7\ \mu g/g$$

Site 3, Drum Storage

Solubility of dioxin (TCDD) = 0.2 -0.6 μg/L (identification and listing of hazardous waste under RCRA, Subtitle C, Section 3001; Health and Environmental Effect Profiles (40 CFR 261). EPA NTIS No. PB81-190019. October 1980)

$\text{Log } K_{ow} = 6.9$ (Briggs, 1981)

$$\text{Log } K_{oc} = 1.029 \log K_{ow} - 0.18 \text{ (equation 36, Table 3)}$$
$$= 1.029\ (6.9) - 0.18$$
$$= 6.920$$

$$\text{or Log } K_{oc} = 0.544 \log K_{ow} + 1.377 \text{ (equation 32, Table 3)}$$
$$= 5.31$$

Averaging logs:

$$\frac{6.920 + 5.131}{2} = 6.016$$

$$K_{oc} = 1.036 \times 10^6$$

DOC, using organic carbon content from Table 6:

$$d = (1.036 \times 10^6)(0.01)(0.2 \times 10^{-3}) \text{ at lowest solubility}$$
$$= 2.07\ \mu g/g$$

and

$$d = (1.036 \times 10^6)(0.6 \times 10^{-3})(0.01) \text{ at highest solubility}$$
$$= 6.22\ \mu g/g$$

The average value for d = 4.145 μg/g

These values assume no degradation. However, the site was active from 1962 to 1970. Data from Harrison and Crews (1983) show that degradation took place. Recent concentration measurements showed a value of 120 ppb, while measurements of a sample held in storage for 10 years had a value of 6,400 ppb. Using Equation (46):

$$\begin{aligned} k &= (\ln C_o - \ln C)/t \\ &= (\ln 6400 - \ln 120)/10 \\ &= 0.398\ \mathrm{yr}^{-1} \end{aligned}$$

For an assumed 14-year residence of TCDD and using the estimated d given above:

$$\begin{aligned} \ln C &= \ln C_o - kt \\ &= \ln 4.145 - (0.398)(14) \\ &= -4.150 \end{aligned}$$

$$\begin{aligned} C &= 0.0158\ \mu g/g \\ &= 15.8\ pg/g \end{aligned}$$

Site 4, Haul Road

Solubility of Arochlor 1260 = 0.080 μg/mL

$$\begin{aligned} \text{Log } K_{oc} &= -0.55 \log (0.080) + 3.64 \text{ (Equation 29, Table 3)} \\ &= 4.243 \end{aligned}$$

$$K_{oc} = 17{,}511$$

$$\begin{aligned} \text{or, } \log K_{oc} &= -0.54 \log (2.345 \times 10^{-8}) + 0.44 \text{ (Equation 30, Table 3)} \\ &= 4.560 \end{aligned}$$

$$K_{oc} = 36{,}318$$

Averaging logs:

$$\frac{4.243 + 4.560}{2} = 4.402$$

$$K_{oc} = 25{,}206$$

DOC, using organic carbon content from Table 6:

$$\begin{aligned} d &= (25{,}206)(0.07)(0.080) \\ &= 141\ \mu g/g \end{aligned}$$

Site 5, Storage pile

Lead and zinc values for this site were taken directly from Roberts and Johnson (1978).

COST CALCULATIONS FOR CONTROLS

1. Vegetative stabilization of a 40-acre landfill

- Assume hydraulic seeding is used, including seed, fertilizer, and wood fiber mulch. From Table 21, the cost is $0.44/m² (Means, 1984) and includes material, equipment, labor, overhead, and profit.

$$40 \text{ acres} \times \frac{4{,}047 \text{ m}^2}{\text{acre}} \times \frac{\$0.44}{\text{m}^2} = \$72{,}000 \text{ (installed capital cost)}$$

- Assume that the vegetative cover has an expected lifetime of 10 to 20 years and requires essentially no maintenance during this period. For a compound interest rate of 10 percent, the capital recovery factors are 0.163 (10 years) and 0.117 (20 years).

Annualized cost (10 yr) = $72,000 × 0.163 = $12,700/yr
Annualized cost (20 yr) = $72,000 × 0.117 = $8,400/yr

2. Synthetic film cover for a dried lagoon (1 acre)

- From Section 4.10.2, the installed capital cost for a synthetic film cover ranges from $1 to $6/m².

$$1 \text{ acre} \times \frac{4{,}047 \text{ m}^2}{\text{acre}} \times \frac{\$1 \text{ to } \$6}{\text{m}^2} = \$4{,}000 - \$24{,}000 \text{ (installed capital cost)}$$

- Assume the synthetic cover has an expected lifetime of 5 years. For a compound interest rate of 10 percent, the capital recovery factor is 0.264.

$$\$4{,}000 \times 0.264 = \$1{,}000/\text{yr}$$

$$\$24{,}000 \times 0.264 = \$6{,}300/\text{yr}$$

3. Chemical stabilization of a drum storage area (190 m²)

- The cost for chemical stabilization is a recurring cost that depends upon the frequency of reapplication. From Table 15, material costs range from about $0.02 to $0.13/m². From Table 16, the rental cost for an emulsion sprayer (200 gal, 5 hp engine) is $34/day. Assume 4 labor hours are required to apply the stabilizer at a cost of $23/hr (includes overhead and fringe benefits). The cost for one application is:

Material $190\ m^2 \times \$0.13/m^2 = \$25$

Labor $4\ hr \times \$23/hr = 92$

Equipment rental $\$34/day \times 1\ day = \underline{34}$

Total $151/application

- Assume monthly applications are required to maintain the desired control efficiency. The annualized cost would be:

$$\frac{\$151}{\text{application}} \times \frac{1\ \text{application}}{\text{mo}} \times \frac{12\ \text{mo}}{\text{yr}} = \$1{,}800/\text{yr}$$

4. Pave 0.5 mile of unpaved road

- From Means (1984), the cost elements are:

Prepare and roll sub-base	$0.74/yd²
Fine grading	$0.43/yd²
Add 3 in. of bituminous paving	$6.15/yd²
Total installed capital cost	$7.32/yd²

(Includes equipment, materials, labor, overhead, and profit)

- Assume a road width of 25 feet.

$$\text{Total area} = 0.5\ \text{mi} \times \frac{5{,}280\ \text{ft}}{\text{mi}} \times 25\ \text{ft} = 66{,}000\ \text{ft}^2\ (7{,}333\ \text{yd}^2)$$

- Total installed capital cost:

$$7{,}333\ \text{yd}^2 \times \$7.32/\text{yd}^2 = \$54{,}000$$

- For a lifetime of 10 to 20 years and a 10-percent interest rate, the capital recovery factors are 0.163 and 0.117.

Annualized cost = $54,000 × (0.117 to 0.163) = $6,300 to $8,800/yr

5. Chemical stabilization of a waste pile with a height of 75 ft and a circumference of 950 ft.

- Calculate the lateral surface area:

$$A = \pi r\ (h^2 + r^2)^{\frac{1}{2}},$$

where

h = height = 75 ft

r = radius = $\frac{950}{2\pi}$ = 151 ft

$A = \pi \times 151\ (75^2 + 151^2) = 80{,}000\ \text{ft}^2$ (1.8 acres)

- From Table 18, Bohn and Johnson (1983) estimated the cost of chemical stabilization of a waste pile as \$888 to \$2,720/acre-yr for various types of stabilizers.

Annualized cost = 1.8 acres × (\$888 to \$2,720/acre-yr) =

\$1,600 to \$4,900/yr.

APPENDIX B

TABULATED VALUES FOR DEGREE OF CONTAMINATION ESTIMATES

TABLE B-1. SOLUBILITY AND K_{ow} FOR SELECTED HAZARDOUS WASTE CONSTITUENTS(a)

Name	Solubility μg/mL	Temperature	K_{ow} (μg/g)/(μg/mL)
Acetaldehyde	$10x10^3$	25°C	1.
Acetonitrile	Miscible	NR	0.46
Acetophenone	$5.5x10^3$	20°C	38.9
Acetyl chloride	Decomposed by H_2O	NA	NA
Acrolein	$400x10^3$	25°C	1.
Acrylamide	$2.1x10^6$	30°C	0.10
Acrylic acid	Miscible	NR	1.35
Acrylonitrile	$73.5x10^3$	20°C	1.38/0.12
Alachlor	242.	25°C	830.
Aldrin	0.025	NR	16,000.
Ammonia	$531x10^3$	NR	1.
Ammonium acetate	$>1x10^6$	25°C	1.
Ammonium cyanide	$1x10^3$(b)	NR	1.
Ammonium methacrylate	$>1x10^3$	NR	0.00025
Antimony pentachloride	Decomposed by H_2O	NA	NA
Antimony trichloride	$6x10^6$	0°C	1.
Aniline	$35x10^3$	25°C	8.
Arsenic	Insoluble	NA	1.
Atrazine	33.	27°C	476.
Benzo(a)anthracene	0.011	NR	427,000.
Benzene	$1.8x10^3$	25°C	135.
2-Chloro-4-Nitro benzoic acid	2.	NR	219.
4-Chloro-3-Nitro benzoic acid	2.	NR	219.
p.-Chloro Sodium salt of benzoic acid	$100x10^3$(b)	NR	0.031
Benzofluoranthene	NR	NR	NR
Benzo(a)pyrene	0.004	25°C	1,096,500.
Benzotrichloride	Insoluble	NR	10,700.
Benzyl chloride	$3.3x10^3$	25°C	426.6
Bicycloheptadiene	$2.8x10^3$	NR	95.5
Bromacil	815.	NR	2.45
1,3-Butadiene	735.	NR	97.72
n-Butyl alcohol	$90x10^3$	25°C	7.59
Cacodylic acid	$75x10^3$	NR	1.
Cadmium	20.	NR	1.
Captan	<0.5	25°C	224.
Carbaryl	65.	NR	230.
Carbofuran	700.	25°C	40./354.8
Carbon tetrachloride	800.	20°C	417.
Chloral	$14.7x10^3$	NR	25.7
Chloroacetaldehyde	$10x10^3$	NR	2.0
Chloroacetic acid	$100x10^3$	25°C	2.45
Chloroaniline (para)	$10x10^3$	20°C	67.61
Chlorobenzene	488.	25°C	690.
Chlordane	0.06	25°C	40,000.
Chlordene	1.85	NR	602.6
Chloro alkyl ether (BCEE)	Insoluble	NA	1.
Chloroform	$8.2x10^3$	25°C	100.
Chloronitrobenzene	500.	NR	316.23
2-Chloroallyl diethyldithiocarbamate (CDEC)	92.	25°C	1.

See notes at end of table

continued

TABLE B-1. SOLUBILITY AND K_{ow} FOR SELECTED HAZARDOUS WASTE CONSTITUENTS

Name	Solubility µg/mL	Temperature	K_{ow} (µg/g)/(µg/mL)
2-Chlorophenol	28.5×10^3	20°C	144.5
3-Chlorophenol	26×10^3	20°C	316.2
4-Chlorophenol	27.1×10^3	20°C	263.0
2 Chloropropane	200.	NR	1.
Chlorotoluene	$<1 \times 10^3$	NR	2,137.9
Chloroxuron	3.7	20°C	1,200.
Creosote	5.	NR	1.
Chromium	20.	NR	1.
Cresol	25×10^3	20-25°C	93.3
Cumene	50.	25°C	5,623.4
Acetone cyanohydrin	10×10^3	25°C	1.
Cyanogen chloride	2.5×10^3	25°C	1.
Cyclohexane	45.	25°C	2,754.2
Cyclohexanone	24×10^3	25°C	1.
Cyclopentadiene	132.	NR	1,380.4
Diazinon	40.	20°C	15.
Dibenzothiophene	1.47	20-25°C	24,000.
o-Dichlorobenzene	123.	25°C	2,511.9
p-Dichlorobenzene	79.	25°C	2,450.
1,2 Dichloroethane	8.7×10^3	NR	31.6
2,4 Dichlorophenol	4.6×10^3	20°C	1,380.4
2,6 Dichlorophenol	0.279	NR	794.3
2,4-D	620.	25°C	645.6
Dichloropropane	2.7×10^3	25°C	100.
1,3 Dichloropropene (cis/trans)	2.8×10^3	NR	1.
2,3 Dichloropropene	100. (b)	NR	1.
Dieldrin	0.25	25°C	800.
Diethyl maleate	12.	NR	25.1
Diethyl methyl phosphorodithionate	100.		1.
Diethylene glycol	Miscible	NR	1.
Diethylene glycol monobutyl ether	1×10^3(b)	NR	1.
Dimethylamine	1×10^6	25°C	0.42
Dimethyl disulfide	1×10^3	NR	7.4
Dimethyl phosphorothioic acid	100. (b)	NR	1.
Dimethyl dithiophosphoric acid	100. (b)	NR	1.
Sym-dimethylurea	$>50 \times 10^3$	NR	0.32
Dinitrobenzene	470.	15°C	41.7
o-Dinitrobenzene	2.1×10^3	25°C	41.7
Dipropylamine	10×10^3	NR	46.8
Dipropyl urea	14.4×10^3	NR	43.7
Disulfoton	25.	NR	1.9
Diuron	42.	25°C	630.9
Epichlorohydrin	66×10^3	25°C	1.
Ethyl mercaptan	15×10^3	NR	15.8
Ethyl acrylate	15×10^3	25°C	10.
Ethyl chloride	4.5×10^3	25°C	26.9
Ethylene diamine	1×10^6	25°C	0.063
Ethylene glycol monoethyl ether	Infinite	NR	1.
Ethylene glycol monobutyl ether	Miscible	NR	1.
Ethyl ether	7.5×10^3	25°C	3.39
Ethylene thiourea	2×10^3	NR	1.

See notes at end of table

continued

TABLE B-1. SOLUBILITY AND K_{ow} FOR SELECTED HAZARDOUS WASTE CONSTITUENTS

Name	Solubility µg/mL	Temperature	K_{ow} (µg/g)/(µg/mL)
Ferbam	120.	NR	14.
Formaldehyde	Miscible	NR	1.
Formic acid	Miscible	NR	0.29
Fumaronitrile	1×10^{6}	NR	0.13
Furan	10×10^{3}	25°C	21.9
Furfural	83×10^{3}	20°C	4.9
Heptachlor	0.056	25°C	8,000.
Hexachlorobenzene	0.035	NR	168,000.
Hexachlorobutadiene	0.005	20°C	40,000.
Hexachlorocyclopentadiene	27.3/0.805	NR	9,772.
Hexachloroethane	50.	NR	18.
Hexachlorophene	0.004	NR	$34.7 \times 10^{6}/676 \times 10^{6}$
Hydrofluoric acid	1×10^{6}	25°C	1.
Hydrogen cyanide	1×10^{6}	25°C	0.56
Hydroquinone	500×10^{3}	25°C	3.55
Isobutanol	95×10^{3}	18°C	7.
Lead	<.01	NR	20,000.
Malathion	145.	25°C	780.
Maleic acid	788×10^{3}	25°C	0.26
Maleic anhydride	163×10^{3}	30°C	0.26
Maneb	200. (b)	NR	1.
Methacrylonitrile	35.7×10^{3}	25°C	251.
Methanol	1×10^{6}	25°C	5.13
Methomyl	34×10^{3}	NR	2.
Methyl chloride	400.	25°C	8.13
Methylene chloride	20×10^{3}	25°C	19.9
Methyl ethyl ketone	100×10^{3}	25°C	1.
Methyl isobutyl ketone	19×10^{3}	25°C	1.
Methyl methacrylate	20. (b)	NR	6.17
Methyl paraoxon	44.	NR	19.0
Methyl parathion	60.	25°C	82.
α Methylstyrene	83.	NR	2,138.
Mononitrobenzene	1.9×10^{3}	25°C	62.
Nabam	$300 \times 10^{3}/20 \times 10^{3}$	NR	60.
α Naphthol	1×10^{3}	25°C	512.9
Naphthoquinone	200. (b)	NR	54.9
Nicotinonitrile	100. (b)	NR	1.62
Nitrodipropyl amine	1×10^{3}(b)	NR	0.63
Nitrofuran	2.3×10^{3}	NR	72.4
Nitrophenol	13.5×10^{3}	25°C	50.1
Diethylnitrosamine	100×10^{3}	NR	3.02
Nitrotoluene (meta)	498.	30°C	245.5
Paraldehyde	120×10^{3}	18°C	14.12
Parathion	24.	25°C	6,400.
Pentachlorobenzene	0.24	22°C	154,000.
Pentachloroethane	500.	NR	1.
Pentachlorophenol (PCP)	14.	NR	102,000.
Pentadiene	10. (b)	NR	30.2
Phenol	67×10^{3}	25°C	31.6
Phorate	50.	NR	18.

See notes at end of table

continued

TABLE B-1. SOLUBILITY AND K_{ow} FOR SELECTED HAZARDOUS WASTE CONSTITUENTS

Name	Solubility µg/mL	Temperature	K_{ow} (µg/g)/(µg/mL)
0,0 Diethyl phophorodithioate	100. (b)	NR	2.82
Phosphorodithioic acid, methylene tetraethyl ester	$1x10^3$(b)	NR	1.
0,0,0 Triethyl phosphorothioate	$1x10^3$(b)	NR	1.
Phosphorous sulphide	$1x10^6$(b)	NR	1.
Phthalic anhydride	$6.2x10^3$	NR	0.24
Polyram	Insoluble	NR	NR
Propionic acid	$1x10^6$	25°C	1.
Propylamine	$1x10^6$	25°C	1.82
Propyl mercaptan	20.	NR	14.
Pyrene	0.135	NR	150,000.
Pyridine	$>1x10^6$	25°C	4.57
Sodium fluoride	$43x10^3$	25°C	1.
Succinonitrile	$130x10^3$	NR	0.16
Sulfide (Ethylsulfide)	$10x10^3$ (b)	NR	20.
2,4,5-T	278.	25°C	4.
TCDD (Dioxin)	$4x10^{-4}$	NR	1.74
TEPP (Tetraethyl pyrophosphate)	Miscible	NR	1.
1,2,4,5 Tetrachlorobenzene	0.3/6.	NR	47,000.
Tetrachloroethane	$3.7x10^3$	NR	398.
Tetrachloronitrobenzene	10. (b)	NR	50,000.
2,3,4 6 Tetrachlorophenol	$1x10^3$	25°C	12,589.
Tetrahydrofuran	Miscible	NR	2.88
Toluene	470.	25°C	117.5
Toxaphene	3.	25°C	825.
Trichlorobenzene	30.	NR	15,000.
1,1,1 Trichloroethane	$4.4x10^3$	20-25°C	158.5
1,1,2 Trichloroethane	200. (b)	NR	158.5
2,4,5 Trichlorophenol	$1.2x10^3$	25°C	5,248.
2,4,6 Trichlorophenol	800.	25°C	4,169.
1,2,3 Trichloropropane	$<1x10^3$	NR	1.
Trichloro,trifluoroethane (Freon)	10.	NR	100.
Triethylene glycol	Infinite	NR	1.
Trifluralin	24.	27°C	220,000.
0,0,S-Trimethyl phosphorodithioate	$1x10^3$ (b)	NR	1.17
Trimethyl phosphate	$1x10^3$ (b)	NR	0.30
0,0,0 Trimethyl phosphorothioate	$1x10^3$ (b)	NR	1.
1,3,5 Trinitrobenzene	350.	NR	23.4
Vernolate	90.	20°C	1.
m-Xylene	130.	NR	1,820.
o-Xylene	175.	25°C	891.
p-Xylene	198.	NR	1,412.
Zineb	10.	25°C	60.

See notes at end of table

NA = Not applicable
NR = Not reported

(a) Nearly all the values in this table are taken from Physical Chemical Properties of Hazardous Waste Constituents, a Draft Report by D.W. Dawson, C.J. English, and S.E. Petty for the EPA's Southeast Environmental Research Laboratory, Athens, Georgia, March 1980. In cases where values were not reported in this document, they were taken from The Handbook of Environmental Data on Organic Chemicals, (2nd edition) by Karel Verschueren. Van Nostrand Reinhold, New York, 1983.

(b) These values are estimates based on the compound's structure.

TABLE B-2 REPORTED VALUES OF K_{oc} AND ASSOCIATED SOIL ORGANIC CARBON CONTENT

Name	K_{oc} (μg/g)/(μg/ml)	Organic Carbon %	Reference
Aldicarb	28	NR	Felsot and Dahm, 1979
	42	2.05	Briggs, 1981
Ametryne	120-960	0.34-3.06	Rao and Davidson, 1982
Amiben	4.2-860	0.35-5.70	Rao and Davidson, 1982
Anthracene	2.6×10^3	NR	Karickhoff, Brown, and Scott, 1979
	16×10^3	NR	Karickhoff, 1981
Atrazine	102 ± 5.8 (c)	9.4-46	Hamaker and Thompson, 1972
	166 (c)	0.1-8.4	Hamaker and Thompson, 1972
	122 (c)	0.6-3.9	Rao and Davidson, 1979
	216	NR	Brown and Flagg, 1981
	4.7-394	0.28-16.7	Rao and Davidson, 1982
Benzene	83	NR	Karickhoff, Brown, and Scott, 1979
	60	NR	Karickhoff, 1981
Bromacil	50	0.06	Gerstl and Yaron, 1983
	25	0.40	"
	29	0.55	"
	32	1.01	"
Captan	198	2.05	Briggs, 1981
Carbaryl	390 (a)	NR	Swann et al., 1983
	370 (b)	NR	"
	104	2.05	Briggs, 1981
	121	2.05	"
Carbofuran	16-39	1.1-10.9	Rao and Davidson, 1982
	100 (a)	NR	Swann et al., 1983
	130 (b)	NR	"
Chlorobenzene	316	NR	Walsh, 1983
Chlorobromuron	546-1,940	1.02-6.05	Rao and Davidson, 1982
Chloroxuron	2.8×10^3 - 6.2×10^3	1.7-11.7	Rao and Davidson, 1982
Chlorpyrifos	6×10^3 (a)	NR	Swann et al., 1983
	10×10^3 (b)	NR	"
	4.6×10^3	NR	Felsot and Dahm, 1979
	31.6×10^3	NR	Walsh, 1983
p-Cresol	79 (c)	NR	"

See notes at end of table

continued

TABLE B-2 REPORTED VALUES OF K_{oc} AND ASSOCIATED SOIL ORGANIC CARBON CONTENT

Name	K_{oc} (μg/g)/(μg/ml)	Organic Carbon %	Reference
2,4-D acid	23 (a)	NR	Swann et al., 1983
	60 (b)	NR	"
	20	NR	Walsh, 1983
	7.9-55	1.02-6.05	Rao and Davidson, 1982
2,4-D amine	109 ± 30(c)	0.6-3.9	Rao and Davidson, 1979
	72-135	0.56-3.87	Rao and Davidson, 1982
DDT	150×10^3(a)	NR	Swann et al., 1983
	44×10^3(b)	NR	"
	1×10^6	NR	Walsh, 1983
Denobil	59-826	0.11-5.54	Rao and Davidson, 1982
Diazinon	227	2.05	Briggs, 1981
Dibenzothiophene	10.2×10^3(c)	0.11-2.38	Hassett et al., 1980
Dicamba	3.8	23.6	Hamaker and Thompson, 1972
	1.2-4.9	2.3-6.0	Rao and Davidson, 1982
Dieldrin	12.8×10^3	2.05	Briggs, 1981
Dimethoate	9	2.05	Briggs, 1981
Dimethylamine	313-528	1.0-6.1	Rao and Davidson, 1982
Diphenylamine	598	0.63-2.5	Briggs, 1981
Disulfoton	5.8×10^2 - 2.5×10^3	0.12-15.0	Rao and Davidson, 1982
Diuron	191	NR	Briggs, 1981
	300	NR	Swann et al., 1983
	902 ± 31.9	12-37	Hamaker and Thompson, 1972
	110-1,370	0.25-12.0	Rao and Davidson, 1982
Fenuron	19-135	1.02-12.0	Rao and Davidson, 1982
	26	NR	Briggs, 1981
Freon	158 (c)	NR	Walsh, 1983
Hexachlorocyclopentadiene	4.26×10^3	NR	Chou and Griffin, 1983

See notes at end of table

continued

TABLE B-2 REPORTED VALUES OF K_{oc} AND ASSOCIATED SOIL ORGANIC CARBON CONTENT

Name	K_{oc} (μg/g)/(μg/ml)	Organic Carbon %	Reference
Lindane	940-1,221	1.6-2.1	Rao and Davidson, 1982
	1,181 (c)	1.1-3.5	Hamaker and Thompson, 1972
Linuron	124-2,670	0.5-12.0	Rao and Davidson, 1982
	229	NR	Briggs, 1981
Malathion	580-4,520	0.5-2.9	Rao and Davidson, 1982
Methyl chloroform	158 (c)	NR	Walsh, 1983
Naphthalene	1300	NR	Karickhoff, Brown, and Scott, 1979
	870	NR	Karickhoff, 1981
	414	NR	Briggs, 1981
Parathion	1039	NR	Briggs, 1981
	1108	NR	Felsot and Dahm, 1979
	3,400-21,000	0.09-0.65	Rao and Davidson, 1982
2,2'4,5,5'-PCB	$500\text{x}10^3$(a)	NR	Swann et al., 1983
	$280\text{x}10^3$(b)	NR	"
Phenanthrene	$12\text{x}10^3$	NR	Karickhoff, 1981
Prometone	294 (c)	NR	Hamaker and Thompson, 1972
Propazine	152	9.4-27.1	"
	162	0.1-7.8	"
	363		Brown and Flagg, 1981
	29-262	0.34-19.98	Rao and Davidson, 1982
Pyrene	$84\text{x}10^3$	NR	Karickhoff, Brown, and Scott, 1979
	$67\text{x}10^3$	NR	Karickhoff, 1981
Quinoline	158 (c)	NR	Walsh, 1983
2,4,5-T	1.05 (c)	NR	Hamaker and Thompson, 1972
	38-123	0.53-3.6	Rao and Davidson, 1982
1,2,4 Trichlorobenzene	$5\text{x}10^3$(c)	NR	Walsh, 1983
Trifluralin	$4.3\text{x}10^3$(a)	NR	Swann et al., 1983
	$9.6\text{x}10^3$(b)	NR	"
Trithion	$8.4\text{x}10^3$ - $9.4\ \text{x}10^4$	0.09-0.65	Rao and Davidson, 1982

See notes at end of table

continued

TABLE B-2 REPORTED VALUES OF K_{oc} AND ASSOCIATED SOIL ORGANIC CARBON CONTENT

Name	K_{oc} (μg/g)/(μg/ml)	Organic Carbon %	Reference
Simazine	25-365	0.34-14.0	Rao and Davidson, 1982
	47	2.05	Briggs, 1981
	159 (c)	10.9-14.1	Hamaker and Thompson, 1972
	126.5 (c)	0.08-4.6	"
	215		Brown and Flagg, 1981

NR = Not reported

(a) K_{oc} measured using the soil slurry method (see Swann et al., 1983)

(b) K_{oc} measured using reverse-phase high performance liquid chromatography (see Swann et al., 1983)

(c) Values are an average of many samples.

TABLE B-3. REPORTED VALUES FOR PHYSICAL PROPERTIES OF SEDIMENTS AND SOILS

Geographic Location	Soil Type	Organic Carbon (%)	Soil Analysis Sand (%)	Soil Analysis Silt (%)	Soil Analysis Clay (%)	References
FL	Eustis fine sand	0.56	93.8	3.0	3.2	Rao and Davidson, 1979
GA	Cecil sandy loam	0.90	65.8	19.5	14.7	"
GA	Small pond sediment - grass watershed	1.6	50.	50.	1.	Karickhoff, Brown, and Scott, 1979
GA	Small pond sediment - wooded watershed	2.3	50.	50.	1.	"
GA	Small river sediment	1.9	90.	5.	5.	"
IA	Webster silty clay loam	3.87	18.4	45.3	38.3	Rao and Davidson, 1979
Onawa, IA	Missouri River Sediment	0.15		10.7	6.8	Karickhoff, 1981
Turin, IA	Loess Sample	0.11		75.6	17.4	"
Story Co., IA	Sarpy fine sandy loam	0.51	77	15	8	Felsot and Dahm, 1979
Story Co., IA	Thurman loamy fine sand	1.07	83	9	8	"
Story Co., IA	Clarion	2.64	37	42	21	"
Story Co., IA	Harps	3.80	21	55	24	"
Story Co., IA	Peat soil	18.36	42	39	19	"
IL	Soil, Fern Clyffe State Park	1.30		71.4	28.6	Karickhoff, 1981
Lorenzo, IL	Illinois River sediment	1.88		42.7	7.1	"
McGlure, IL	Mississippi River sediment	1.48		55.4	42.9	"
Leavenworth, IN	Ohio River sediment	0.95		48.7	35.7	"
Stanton, ND	Missouri River sediment	2.07		41.8	55.2	"
Lake Oahe, ND	Missouri River sediment	2.28		35.4	31.0	"
Big Bend Lake, SD	Missouri River sediment	0.72		31.2	68.6	"
Ceredo, WV	Soil eroded hillside	0.48		34.4	63.6	"
NR	Norwood sandy clay (Typic Udifluvent)	0.81	48.2	15.2	36.6	Donnelly, Brown, and Scott, 1983

continued

TABLE B-3 REPORTED VALUES FOR PHYSICAL PROPERTIES OF SEDIMENTS AND SOILS

Geographic Location	Soil Type	Organic Carbon (%)	Soil Analysis			References
			Sand (%)	Silt (%)	CLay (%)	
NR	Bastrop Clay (Udic Paleustalf)	0.58	60.3	10.0	29.7	Donnelly, et al., 1983
NR	Aiken	3.0	21	36	43	Hoffman and Rolston, 1980
NR	Columbia coarse loam	0.46	12	25	63	"
NR	Panoche fine loam	0.83	29	43	28	"
NR	Redding fine	2.07	10	40	50	"
NR	Sacramento very fine (Montmorillonitic)	4.98	51	36	13	"

NR = Not reported